APPLICATION OF DYNAMIC LANE GROUPING AND ARTIFICIAL INTELLIGENCE TECHNIQUES IN PREDICTING THE OPTIMUM LANE GROUPS AT ISOLATED SIGNALIZED INTERSECTIONS

BY

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To My Beloved Parents Jamal and Ibtisam

My Wife Hanan

My Children Ahmad and Jana

My Sister Fatimah

My Brothers Ribhe, Mujahed and Tariq

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ABSTRACT

Full Name : Khaled Jamal Abdeljaber Assi

Thesis Title : Application of Dynamic Lane Grouping and Artificial Intelligence Techniques in Predicting the Optimum Lane Groups at Isolated Signalized Intersections

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Signalized intersection is an important element of any road network. Its operations impact adversely the environment and safety and further affect significantly the performance of the whole road system. A considerable variability in traffic demand is expected at most signalized intersections in urban areas. Most of such intersections nowadays are prone to the phenomenon of tide traffic where different traffic movements at each approach (left, through and right) are fluctuating significantly with time. This phenomenon has a significant role in degrading intersections performance and results in congestion along with excessive emissions of harmful gases. This study was conducted to investigate the effectiveness of applying dynamic lane assignment strategy, which is also known as dynamic lane grouping, to optimize signal timing plans. The concept of Dynamic Lane Grouping (DLG) has been introduced to mitigate such operation problems. MATLAB environment was used to build an optimization model to find the optimal lane groups at all intersection approaches for hypothetical massive traffic demand combinations using an objective function of minimizing intersection delay. A comparison was conducted between the average intersection delay for DLG and Fixed Lane Grouping (FLG) at different demand combinations. It is observed that applying DLG yields a significant reduction in average intersection delay compared to FLG. This study also introduced a plausible quick method to predict the optimum lane group in the field instantaneously using the percentage of turning movements at the approach without conducting massive calculations. On the other hand, interviews were conducted to explore the drivers' response to the information about the existing configuration when disseminated via Variable Message Signs (VMS). The effect of drivers' characteristics, such as age, occupation, driving experience and education level on their response to VMS, was

statistically tested using contingency analysis. It was found that the most significant variable that will affect the drivers' understanding of VMS is the level of education. Moreover, the Artificial Neural Networks (ANN) model was developed to predict the optimal lane group combinations for any turning movement combinations with an average accuracy of 92%.

ملخص الرسالة

الاسم الكامل: خالد جمال عبد الجابر عاصي

عنوان الرسالة: تطبيق ألية المسار الديناميكي المتغير وتقنية الذكاء الاصطناعي لاكتشاف افضل اتجاه للمسارب على التقاطعات المرورية.

التخصص: الهندسة المدنية

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تعتبر التقاطعات ذات الاشارات الضوئية من اهم عناصر شبكة الطرق حيث ان الحركة المرورية عليها لها اثر كبير على البيئة وعلى مجمل شبكة الطرق. معظم التقاطعات المرورية هذه الايام تتعرض بشكل كبير لظاهرة تذبذب الحركة المرورية خلال اليوم مما له الأثر السلبي الكبير على تثبيط الحركة المرورية على التقاطع وما يترتب عليه من ازدحامات مرورية خانقة وانبعاث الغازات الضارة بالبيئة. هذه الدراسة تهدف الى دراسة سبل تطبيق ألية المسرب الديناميكي (DLG) وأثرها في التخفيف من المشاكل الناجمة عن تذبذب الحركة المورية خلال اليوم على التقاطعات ذات الاشارات الضوئية. تم استخدام برنامج MATLAB لبناء نموذج يعمل على اختيار افضل اتجاه للمسارب (يمين، أمام، يسار) على التقاطعات ذات الثلاث ارجل والتقاطعات ذات الاربعة أرجل باستخدام النسبة المئوية من السيارات على كل اتجاه (يمين، أمام، يسار) حيث ان اتجاه المسارب الذي تم اختياره بواسطة النموذج هو الذي يتسبب بأقل نسبة تأخير للسيارات مقارنة باتجاهات المسارب الاخرى. بمقارنة التأخير الناتج عن تطبيق ألية المسرب الديناميكي مع التأخير الناتج عن عدم تطبيقه لوحظ ان تطبيق ألية المسرب الديناميكي لها الاثر الكبير في تقليل التأخير للسيارات على التقطعات المرورية. من ناحية أخرى تم عمل مقابلات شخصية مع 300 سائق لاكتشاف مدى فهم السائقين للوحات الالكترونية المتغيرة (VMS) المستخدمة في توضيح اتجاهات المسارب. بناء على المعلومات التي تم جمعها من هذه المقابلات، تم دراسة تأثير بعض العوامل مثل العمر، الدرجة العلمية، المهنة وعدد سنوات القيادة على فهم السائقين للوحات الالكترونية المتغيرة وقد وجد ان اهم هذه العوامل هو مستوى التعليم . اضافة الى ذلك، تم استخدام الذكاء الاصطناعي لبناء شبكة عصبية اصطناعية (ANN) لاستخدامها في اكتشاف افضل اتجاه للمسارب لأي تعداد مروري في اي تقاطع مشابه للذي تم استخدامه في هذه الدراسة ولقد بلغت نسبة دقتها %92

CHAPTER 1

INTRODUCTION

1.1 Background

Signalized intersection is an important element of any road network. Its operations impact adversely the environment and safety and further affect significantly the performance of the whole road system. Continuous growth in traffic demand with the limited capacities of the existing roadway facilities has brought many challenges, such as high gas emissions and higher energy consumption along with ever-increasing congestion. Most signal control strategies worldwide assume fixed lane utilization at intersection approaches, which means that each lane serves a specific movement without considering the variation in demand with time. This approach is called fixed lane grouping (FLG).

A considerable variability in traffic demand is expected at most signalized intersections in urban areas [1]. Most of such intersections nowadays are prone to the phenomenon of tide traffic where different traffic movements at each approach (left, through and right) are fluctuating significantly with time. This phenomenon has a significant role in degrading the intersections performance and results in congestion along with excessive emissions of harmful gases. The traditional methods for signal timing optimization at signalized intersections, such as Webster method [2], focus on minimizing vehicles delay, assuming a fixed lane configuration. Based on peak hour demand, traffic lanes are usually assigned permanently to different movements at each approach of the intersection. However, due to the fluctuation in the relative turning movement demand at the same approach, the signal optimization process may result in long signal cycle durations which deteriorate the level of service at signalized intersections at other time periods of the day.

Intelligent Transportation Systems (ITS) have been receiving increasing interest since they can enhance traffic operations and lead to a significant gain in mobility and sustainability as well. This research concentrates on the application of ITS at intersections to improve their mobility performance. It aims to investigate the effectiveness of applying a dynamic lane assignment strategy, which is also known as dynamic lane grouping, to optimize signal timing plans. The concept of Dynamic Lane Grouping (DLG) has been introduced by many researchers to mitigate such operation problems. DLG is a technique that allows dynamic changing of lane utilization in response to the changes in the turning movement percentages at each approach.

Dynamic lane grouping is one of the ITS applications in which the lane allocation depends mainly on the real-time turning movement demand [3]. Dynamic lane assignment is proposed to improve the performance of intersections. For instance, fluctuation in demand at different times of the day can cause long queues as shown in Figure 1-1 in which a high volume of left turning vehicles is served only by one exclusive left turn lane.

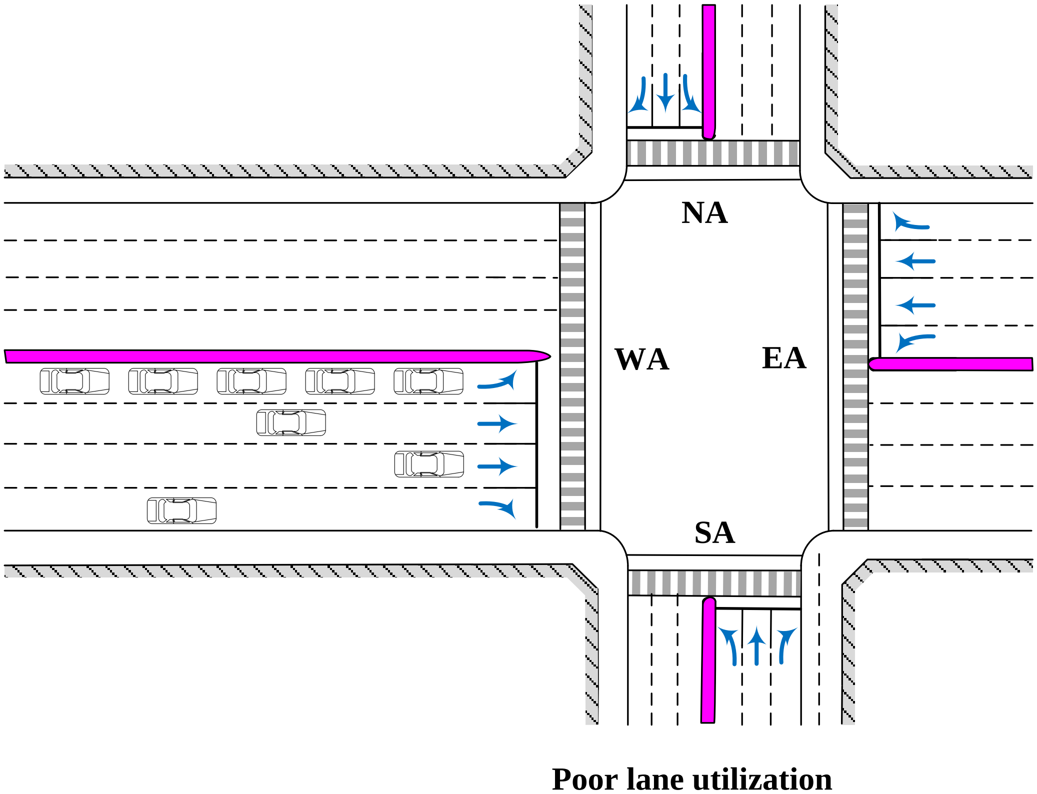


Figure 1-1 Poor Lane Utilization

Dynamic lane assignment is proposed to solve these kinds of problems since it will provide an improved lane utilization by dynamically allocating more lanes for the left turn vehicles at a time when such turning movement is high, as shown in Figure 1-2. This will lead to a better time space allocation and capacity enhancement for the left turn movement.

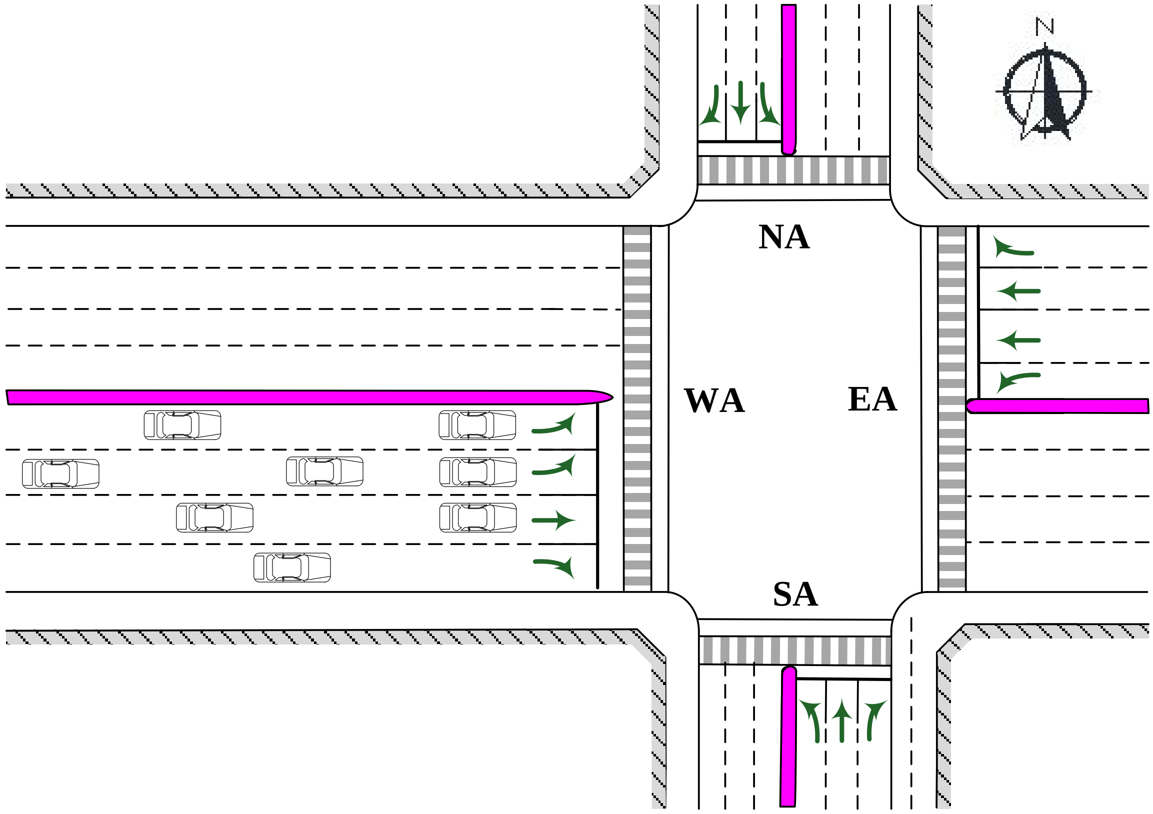


Figure 1-2 Improved Lane Utilization

MATLAB environment was used to build an optimization model to find the optimal lane groups at intersection approaches for hypothetical massive traffic demand combinations. Consequently, a relationship between optimum lane groups and turning movements was identified which, hopefully, will encourage practical application of the DLG principle. Artificial Neural Networks (ANN) technique was used to build a model for signalized intersections, which can be used to predict the optimal lane group for each approach for any demand.

The applicability of dynamic lane grouping in real life practice is considered as a major concern of this new technique. Variable Message Signs (VMS) can significantly support the implementation of DLG by providing drivers before reaching the intersection with real-time information about the existing lane group configuration at the targeted approach.

This research looks for quick methods to find the optimum lane group for 3-lane and 4-lane approaches using the percentage of turning movements. Moreover, it aims to explore the drivers' response to the information about the existing configuration when disseminated via VMS.

1.2 Problem Statement

The growth of urban automobile traffic has led to a serious traffic congestion in most cities. Since travel demand increases at a rate often greater than the addition of road capacity, the situation will continue to deteriorate unless better traffic management strategies are implemented. Ever increasing demand for travel and using the existing road facilities with restricted capacities caused various challenging problems in our daily life, including a continued increase in traffic congestion that causes high energy consumption and pollutants' release. In urban areas, congestion at peak hours is quite commonly occurring near or around the signalized intersections, which represents one of the most important elements of any road network. Improper lane utilization is the major cause of performance deterioration at signalized intersections, which will increase the average delay per vehicle, queue length and gas emissions.

Choosing the proper optimization technique for lane assignment will significantly mitigate these problems. The main concentration of this study is to find a quick method to apply the DLG technique and to explore the drivers' response to the information about the existing configuration when disseminated via variable message signs (VMS) by conducting interviews.

1.3 Study Objectives

The main objective of this study is to develop a new technique which can be used to predict quickly the optimum lane group for any approach at signalized intersections. The other objectives of this study are as follows:

1. Evaluate the possible benefits of applying dynamic lane grouping (DLG) at isolated intersections based on previous international studies.
2. Produce a massive simulated traffic data set for a typical 4-leg intersection, encompassing a wide spectrum of lane volume levels and turning movement combinations.
3. Write a MATLAB code to compute the optimum lane grouping for each case of simulated traffic conditions using all possible lane grouping alternatives based on minimizing intersection delay.
4. Suggest possible artificial intelligence techniques to predict the optimum lane group for any traffic demand.
5. Assess the expected level of drivers' compliance with DLG, if introduced with Variable Message Signs (VMS) through a questionnaire survey.

1.4 Methodology

The previous objectives were attained in the following steps:

1. A comprehensive literature review about the application and evaluation of Dynamic Lane Grouping (DLG) was conducted.
2. A hypothetical massive traffic data set was generated using a MATLAB code.
3. A MATLAB code was developed to compute the optimal lane grouping based on average intersection delay for all possible lane groupings.
4. The developed MATLAB code was executed on the simulated traffic data to identify the optimal lane grouping.
5. Neural network (NN) was used on a sample of this traffic data set and the corresponding output was used to train a neural network model to predict the optimum lane group. Another sample of the traffic data set was used for the validation process.
6. A questionnaire survey and field interviews were conducted with a sample of drivers to study the possible level of compliance with DLG.
7. A statistical analysis was conducted based on the data collected from the survey to find the significant factors that might influence the drivers' compliance with DLG and to evaluate the effectiveness of using VMS to introduce DLG.

1.5 Organization of the Dissertation

This section provides the organization of the remaining chapters of this dissertation. Chapter 2 reports the literature on demand fluctuation at signalized intersections and the need for dynamic lane grouping strategy at these intersections. Chapter 2 also reports the literature on using variable message signs and the applications of artificial neural networks in transportation engineering. Chapter 3 provides a description about model formulation and assumptions. Chapter 4 explains the concept of Feedforward Neural Network and ANN model development with its performance evaluation. Chapter 5 provides an evaluation for using variable message signs to apply dynamic lane grouping through driver interviews. Chapter 5 also describes the survey design and the sample size used and, finally, it provides a statistical analysis of the obtained results. Chapter 6 provides the conclusions and summary of this work and prospective future research works related to this study.

CHAPTER 2

LITERATURE REVIEW

The literature review covers many topics. The first topic is about cycle length optimization. Then, it will cover the demand fluctuation at signalized intersections and its effects on degrading the performance of the intersections. Furthermore, the literature review section covers the application of dynamic lane assignment at signalized intersections and its impact on mitigating the fluctuating demand problems such as delays and stops. The other parts will discuss the use of artificial intelligence techniques such as neural networks in transportation engineering and pre-signalization. The last topic is about the impact of applying dynamic message signs on the drivers' behavior.

2.1 Cycle Length Optimization

Traffic signals are a common form of traffic control used worldwide as they have a significant role in achieving safer and efficient performance at intersections. Many researches have been performed to study the effectiveness of applying different signal timing optimization models on the performance of signalized intersections using many measures of effectiveness such as vehicle delay, number of stops, level of service and fuel consumption as shown in the following paragraphs.

Park and Kamarajugadda [4] conducted a study to develop a genetic algorithm optimization model to optimize signal timing at signalized intersection, considering the day-to day-traffic demand fluctuation. They compared the results of the new model with those of computerized softwares such as TRANSYT-7F and Synchro based on the produced delay.

They found that signal timing plans generated from the genetic algorithm optimization model are superior.

Li [5] conducted a study to optimize the traffic signal timing at isolated intersection. He found that using nonlinear programming is very complex to deal with such problems and the global optimal solution cannot be guaranteed. Hence, they used binary integer programming instead of nonlinear programming. He found that his models are superior compared to other previous models since it needs less computational time.

Tong et al. [6] conducted a study to build an optimization model for signal timing at oversaturated intersections. They used a stochastic programming (SP) approach, which is used mainly in a problem that considers uncertain parameters such as the fluctuation in traffic demand at the intersection. After building the model, they compared the results of their stochastic programming model with that of a conventional deterministic linear programming model. They found that the SP model is better in describing the uncertainty of traffic flow and outperforms the linear programming model as the SP model can generate signal timing plans that better utilize the green time and offer significantly improved intersection performances; however, it needs more computational time.

Benekohal et al. [7] conducted a study to compare between Highway Capacity software (HCS), Synchro, PASSER and CORSIM at pre-timed isolated signalized intersection. The comparison was based mainly on the amount of the delay reduction that materialized when optimized signal settings were implemented. The comparison was done under two conditions: the base condition in which the existing signal settings and traffic volumes were modeled, and the optimized conditions for the optimized signal settings. It was observed that Synchro resulted in significant reduction in delay after optimization compared with the other softwares.

Portugais [8] made a study to compare between the optimized signal timings resulting from Transyt-7F and Vistro based on different performance measures such as Level of Service (LOS), control delay and queue lengths. Based on these performance measures, it was concluded that Transyt-7F outperformed Vistro.

Coll et al. [9] made a study to create a new adaptive system for the signal control problem using a linear programming model. The objective function of the developed model is to minimize the queue length. Real-time sensors were installed at the intersection to provide the traffic information. They found that the new linear programming model is efficient in reducing the queue length and needs short computational time.

It can be observed from the previous studies that the average delay can be considered as one of the important measures of effectiveness, which can be used to find the optimal cycle length. Hence, in this study, the average intersection delay will be used to predict the optimal cycle length for any lane group combination and percentage of turning movements.

2.2 Demand Fluctuation at Signalized Intersections

Most of the intersections nowadays are prone to the phenomenon of tide traffic where different traffic movements at each approach (left, through and right) are fluctuating significantly with time of the day. This phenomenon has a significant role in degrading intersections performance and results in congestion along with excessive emissions of harmful gases.

Traffic planning, operation and control have always a critical concern in the variation in traffic origin-destination demand. A data set collected from 11 intersections in Milwaukee was used to find the Coefficient of Variation (CV) for the peak hours. It was found that the Coefficient of Variation ranged from .048 to .155. These values were applied to volumes at a simulated intersection to quantify the effect of traffic fluctuation on intersection performance. It was concluded that traffic volume variations deteriorate the service levels at signalized intersections [10].

Tarko and Perez-Cartagena [11] studied the variation in traffic demand using 45 intersections in the Indiana state, USA. They investigated both the temporal and spatial variations in Peak Hour Factor (PHF). The authors studied two types of variability: day-to-day and site-to-site, and they found that the day-to-day variability of PHF is as strong as the site-to-site variability. On the other hand, they developed a new model to estimate PHF using the hourly volume, the community population and time of the day as inputs [11].

It can be observed from the previous studies that the signalized intersection can be exposed to traffic fluctuation during the day, which may degrade the performance of signalized intersection. This finding encouraged the researchers to find a new technique such as dynamic lane grouping (DLG) strategy to mitigate the problems of tidal traffic.

2.3 Dynamic Lane Grouping Strategy

The concept of Dynamic Lane Management (DLM), as a congestion relief scheme, has intensively been applied in freeway operation through the opening of hard shoulders to traffic when demand is high. This policy proved to have significant effects on reducing travel time and improving safety [12]. Empirical observations in Hessen, Germany show that using temporary hard shoulder as a traffic management technique improved the safety as it reduced the accident rate by 12%. On the other hand, this technique increased travel speeds and decreased travel time losses [13]. The UK Highways Agency implemented the strategy of active traffic management (ATM) system as a pilot scheme over the 17 km stretch of the M42 highway (3 lanes + hard shoulder) that allows the operators to open the hard shoulder dynamically to traffic at rush hours of the day [14]. A before and after study pointed out significant improvements in peak period travel conditions. Moreover, travel times were reduced by an average of 24% (northbound) and 9% (southbound). The focus of these studies is mainly on links (the road section and road network).

Reversing the lane is another method to increase the capacity of the road and to mitigate the congestion problem without adding extra lanes. In this strategy, traffic flow is being reversed along a lane and temporarily increases the throughput of the road. Studies show that this lane reversal was conducted statically under specific conditions and specific times of the day [15]–[17]. Recent studies show that if the reversible lane strategy is applied dynamically in response to variation in the traffic, the efficiency of the strategy is enhanced significantly up to 72% [18].

Many studies have been performed to evaluate the effectiveness of different techniques rather than dynamic lane assignment in reducing the congestion and increasing the capacity at signalized intersection, such as using the indirect right turn technique [19], left turn waiting areas [20] and adding through lanes [21].

The day to day and hour to hour traffic volume variations enhanced the need to assign the lane dynamically in different time periods in order to match the supply with fluctuating demand. While traffic demand variation on an intersection significantly increases, changing the lane configuration can act effectively in reducing the delay [22].

Few studies were conducted worldwide to investigate the effectiveness of applying Dynamic Lane Grouping (DLG) technique at signalized intersections subjected to high fluctuation in demand. The most recent study about DLG was conducted by Peng “Patrick” Su et al. [23] in Virginia, USA. They developed a criterion for identification of those signalized intersections which are likely to benefit from DLG. They came up with a four screening criteria, namely the safe turning geometry criteria, volume change criteria, volume/lane criteria and volume/capacity criteria. These criteria were coded into a Java based software, which imports Synchro output files and reports in which the intersections were flagged by each criterion. The study shows that the volume/capacity was the most effective criterion among others. They also conducted a case study on the application of DLG, which shows a 15% reduction in overall intersection delay [23].

Ding et al. [24] developed a model to optimize lane use for isolated signalized intersections with variable lanes (lanes which can be used dynamically for different movements) and evaluated this model based on its ability in minimizing the intersection delay. A hypothetical four-approach signalized intersection with at least one variable lane at each approach was used as a case study. The authors assumed that on each approach, there is at least one left-turn lane and one through lane (or shared through and right-turn lanes). They used the cycle lengths of 60 sec and 150 sec as minimum and maximum cycle lengths, respectively. Highway capacity manual procedure for delay calculations was used in this study. They concluded that the proposed model can reduce the average delay and improve the efficiency of the intersection; however, the model was applied at one lane at each approach.

Zhang and Wu [3] and Wu et al. [3], [25] analyzed the effects of DLG at one approach of a hypothetical isolated signalized intersection, assuming predefined demand levels and fixed cycle length of 120 sec using the objective function of minimizing the maximum saturation flow ratio. It was concluded that the DLG strategy improves the performance at signalized intersection by reducing the average vehicle delay and number of stops. Wu et al. [25] made a study to evaluate the benefits of dynamic lane grouping strategy at an isolated intersection using PARAMICS microscopic simulation. They used the same mathematical formulation and numerical analysis of Zhang and Wu [3]. They concluded that dynamic lane grouping strategy can reduce the intersection delay and number of stops. In addition, dynamic lane assignment has positive impacts on the environment, such as reducing gas emissions and energy consumptions, even though they used a fixed cycle length and applied the model at one approach only for simplicity of illustration.

Li et al. [26] developed a dynamic lane use model at a four-approach signalized intersection that was subjected to fluctuation in demand, assuming that the total number of approaching lanes can be changed in consideration of the reversible lanes. The developed model was evaluated by using the VISSIM Simulation Software. It was concluded that the new model has a great effect on reducing the saturation flow ratio of time-space resources by optimizing lane-use assignment and signal phase plan simultaneously.

Zhong et al. [27] conducted a study to investigate the impacts of applying dynamic lane assignment upon the time allocation at a single approach of a hypothetical signalized intersection. An optimization model based on time-space resource combination was proposed. Through numerical analysis, it was concluded that dynamic lane assignment produces an optimum benefit scheme based on dynamic lane functional partition within a given traffic demand range. This optimum scheme showed a significant decrease in traffic delay. However, they neglected the right-turn movement in their model and did not consider shared lanes as well.

Najjar [28] conducted a study to investigate the effectiveness of applying DLG at 4-approach signalized intersection. He applied DLG at all approaches of the intersection accompanied by signal timing optimization, assuming a fixed percentage of right turn vehicles with a massive number of hypothetical percentages of through and left turning traffic at all approaches. He concluded that applying DLG along with signal timing optimization can enhance the performance of the signalized intersection by reducing the intersection delay.

Researchers in the above studies showed that applying DLG has a positive impact on the performance of signalized intersection in terms of reducing delays and number of stops. Nevertheless, their studies were done based on many assumptions, such as using fixed cycle length, ignoring the presence of shared lane and assuming that the demand variation will occur at one approach only. Also, it can be observed that there is a gap in the literature as there is no researcher who has tried to develop DLG for all approaches of the intersection combined with signal timing optimization and consideration of shared lanes. Moreover, the previous literature indicates that almost all of the researchers concentrated on evaluating the benefits of applying DLG at signalized intersections. However, very little attention was given to the method of identifying quickly the optimum lane group. This research will try to fill this gap by developing a new DLG model for all approaches with signal timing optimization considering shared lanes and then trying to find a reasonable mechanism for applying DLG strategy.

2.4 Pre-signalization

Pre-signalization is a proposed technique that can be used to facilitate the process of applying DLG strategy. The idea of the pre-signals is to give priority to a specific movement or mode before reaching the main signal. Many studies have been conducted to evaluate the pre-signal near the signalized intersection.

Guler and Menendez [29] conducted a study to evaluate the effectiveness of applying pre-signals for bus priority at oversaturated signalized intersections by placing a pre-signal upstream of the main signal. This pre-signal will give the bus priority to move to the main signal without encountering conflict maneuvers from cars as shown in Figure 2-1.

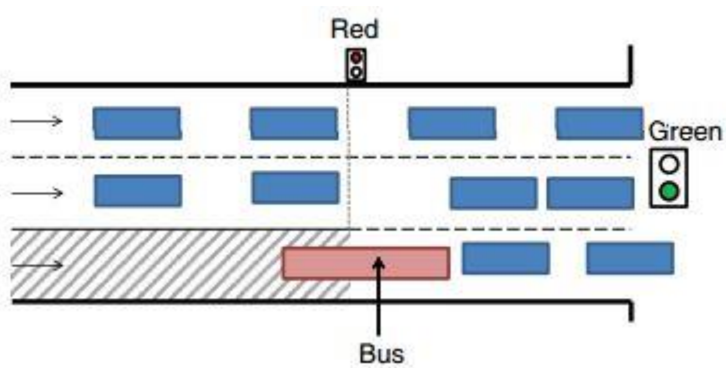


Figure 2-1 Schematic Diagram of intersection with upstream pre-signal [29]

Queuing theory was used to estimate the person hours of delay, which was used as a performance measure. It was concluded that applying pre-signals can reduce the person hours of delay and enhance the performance of the whole system.

Zhao et al. [30] studied the effect of using exit lanes for left turn control (EFL). The basic idea of EFL is to use some of the lanes in the opposite direction as an exit lane for left turn vehicles during various periods using pre-signals as shown in Figure 2-2.

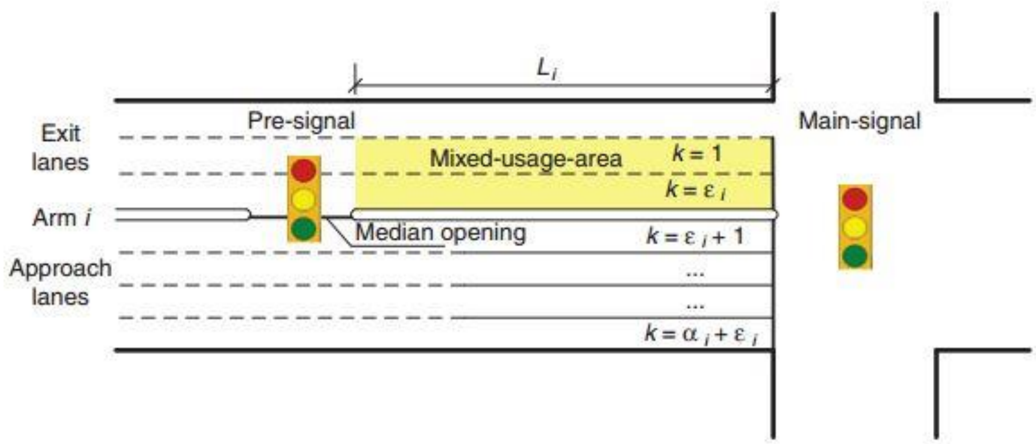


Figure 2-2 EFL control concept [30]

A mixed integer nonlinear programming model was developed to optimize the intersection layout and the timing of both the main signal and pre-signal. The results of VISSIM simulation showed that EFL significantly increased intersection capacity and decreased total delay.

Vieira et al. [31] conducted a study to evaluate the impacts of introducing pre-signals near the saturated signalized intersections in Braga, Portugal. A microsimulation model was developed using Simio to conduct a comparison between the performance measures before applying pre-signals and after applying pre-signals. The results showed that applying pre-signals decreased the average delay and queue length.

Chowdhury [32] conducted a study in New Jersey to evaluate the effectiveness of applying pre-signal near the New Jersey jug-handle intersection (NJJI), which is an unconventional intersection scheme, and eliminate direct left turn. CORSIM was used to develop a microsimulation model to evaluate the operational performance of NJJI with and without pre-signals. The results of the simulation study revealed that applying pre-signals at NJJI increased the main intersection capacity and reduced the stopping time, emission level and fuel consumption.

It can be observed from the previous studies that pre-signals significantly improved traffic operations while increasing intersection capacity. Hence, pre-signals represent a possible technique that can support the implementation of DLG strategy.

2.5 Variable Message Signs

One of the most fundamental technologies available for displaying traffic-related information from the roadside is the Variable Message Signs (VMS). VMS signs are intended to provide en-route real-time information to the drivers and alert them of sudden or unexpected changes in traffic conditions to reduce congestion, enhance safety and improve system performance. Many studies have been performed to investigate the effects of VMS on traffic behavior. The driver expectations and the credibility of the information must be considered when using VMS. With driver expectations, it means that the system has to work and show correct messages because the drivers expect to get updated information.

2.5.1 Effects of VMS on improving traffic operations and safety

Barnard et al. [33] explained that Variable Message Signs (VMS) offer an increase in traffic safety by their ability to deliver messages to motorists to warn them of hazards ahead, such as traffic congestion, incidents (accidents, broken vehicle, bad weather conditions), road works and Dynamic Traffic Management (lane closures, speed management, journey times/route choice). The information is most often displayed in real time and can be controlled either from a remote centralized location or locally at the site.

In a driving simulator study by Dos Santos [34], a possible reduction of rear-end collisions was concluded as a result of using a combination of VMS and variable speed limits. Other studies, such as Borrough [35] and Lee et al. [36], highlighted the possibility of decreasing the number of crashes as a result of applying VMS. The effect of VMS is not limited to safety but expands to reducing travel time, alleviating congestion and improving system performance [37]–[39].

Issa [40] made a study to investigate the effects of using VMS on introducing the technique of changing lane assignment at signalized intersection using ARINA simulation. He concluded that the queue time was reduced during both peak periods due to VMS usage. Also, he found that using VMS as a tool for dynamic lane assignment at signalized intersection proved to be quite promising.

2.5.2 VMS Understanding and Abidance Evaluation

In a recent survey [41] conducted in Missouri, the drivers' response to VMS along a rural freeway was evaluated through a questionnaire. The study revealed that 94% of the surveyed drivers claimed that they will abide with the instructions and suggestions of VMS.

A driver questionnaire conducted to evaluate the impact of VMS on a freeway segment in Wisconsin [42] showed that approximately 70% of the respondents would alter their route based on traffic information displayed on VMS. Furthermore, the same study indicated that the drivers consider VMS useful in reporting weather status and traffic conditions.

In a study by a telephone survey in the Los Angeles area [43], it was indicated that about 70% of the interviewed commuters would divert to an alternative route if adequate traffic information were provided to them. This is in accordance with Wang et al. [44], who concluded that more than 70% of the drivers were sometimes influenced by VMS information.

Hoye et al. [45] questioned the effectiveness of congestion warning messages via VMS and concluded that incident information is the most useful kind of information that can be disseminated via VMS.

Chatterjee [46] investigated the driver response to variable message sign in London. The data were collected by employing a questionnaire survey. They used a logistic regression analysis. The developed models indicate that the location of the incident and the message content are important factors influencing the probability of diversion. Erke et al. [47] observed the impacts of route guidance VMS on driver behavior at two sites on a motorway in Oslo. They found high compliance with the messages on the VMS, in which approximately 20% of the vehicles changed route choice according to VMS suggestions.

Peng et al. [48] made a study about motorists' response to VMS in Wisconsin. On-site user survey was conducted to collect the required information. It was found from the data analysis that more than 65% of the surveyed drivers changed their route at least once per month because of the information received from the VMS.

Schiesel and Demetsky [49] tried to determine the effect of Dynamic Message Signs (DMS) system on driver behavior in changing his route in Virginia. Data was collected using loop detectors. They concluded that the average diversion percentage was very low due to different reasons, such as weak message displayed on the system and the unwillingness of the drivers to divert.

Peeta et al. [50] made a study to investigate the effect of different message contents on driver response to VMS in Indiana. The study was conducted via an on-site survey in the form of a questionnaire. Logit models were developed for drivers' diversion decision. It was concluded that the level of detail of relevant information significantly affects the drivers' willingness to divert.

It can be observed from the previous literature that using VMS can enhance the performance and safety of the traffic network. Also, different studies in different countries showed that a high percentage of drivers understood and complied with the information disseminated via VMS. These findings introduced VMS as a strong proposed technique, which can significantly support the implementation of DLG by providing drivers before reaching the intersection with real-time information about the existing lane group configuration at the targeted approach.

2.6 Artificial Neural Networks

Because of its capability to work without prior information about the relationships between inputs and outputs and its ability to model nonlinear data, Artificial Neural Networks

(ANNs) have been widely used to solve various transportation problems. The basic structure of ANN is given in Figure 2-3.

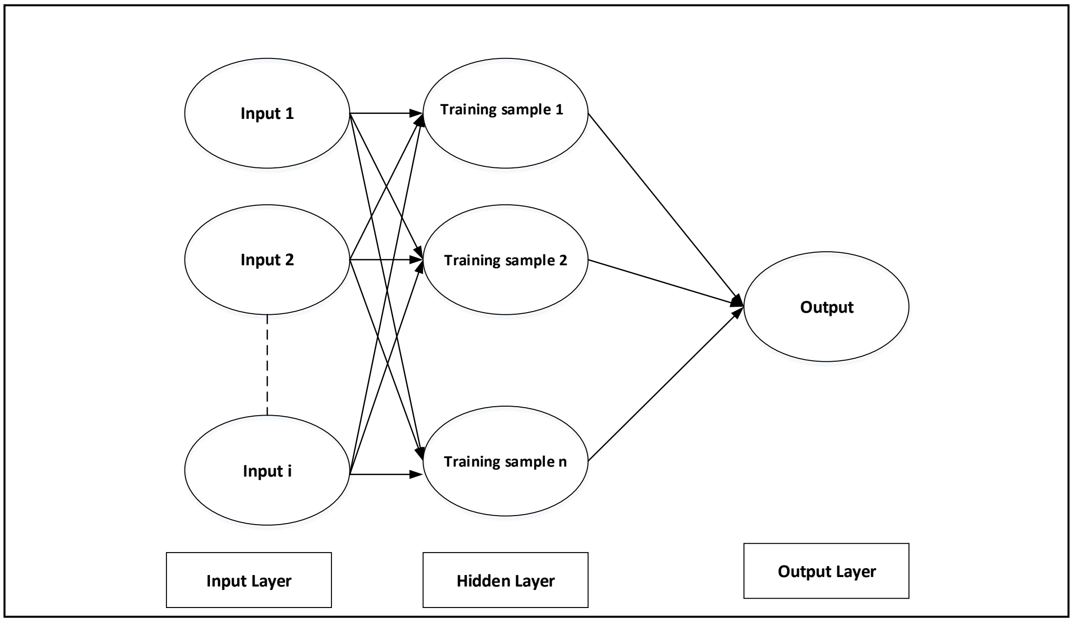


Figure 2-3: Basic structure of ANN

It can be observed from Figure 2-3 that the basic structure of any ANN consists of three layers: input layer in which the number of neurons equal to the number of input parameters, hidden layer which collects the input and feeds it forward after summation and application of the chosen activation function, and output layer which has the same number of units as the model outputs. There are several types of ANN, the simplest type of which is known as Multi-Layer Perceptron (MLP) or feedforward backpropagation ANN since the signals travel in one way only, from the inputs to the output layer without looping. ANNs are capable of estimating nonlinear, stochastic variable data sets. ANNs are composed of interconnected processing units called nodes, which consist of layers and are all added with weighted connections. For any data training and learning procedure, ANNs give a network which can adjust the connecting weights and associated accuracy. If sufficient number of hidden units (neurons) are available, ANNs have the ability to estimate any function with desired accuracy [51]. The commonly used type of ANN is Radial Basis Function Neural Networks (RBF), which are used mainly for the function approximation. It has the same structure of the basic ANN but the hidden layer contains a nonlinear activation function instead of the linear one.

Rahman [52] tried to apply different ANN techniques to predict the traffic flow at isolated intersection. He concluded that applying ANN techniques can be efficient and promising for predicting traffic flow at isolated intersections. Gazder and Ratrout [53] conducted a study to model the mode choice behavior on King Fahd Causeway, which connects the Kingdom of Saudi Arabia and Bahrain. Logit model is a statistical technique commonly used for choice modelling. They found that combining the logit models with ANN techniques will give better performance than single logit models.

Smith and Demetsky [54] made a study to compare between ANN model and the traditional historical time-series model and data based algorithm. They found that the ANN model was clearly superior in forecasting the future traffic volumes.

Ulbricht [55] conducted a study to check whether neural networks (NN) can solve the task of short-term traffic forecasting. He concluded that NN can solve this task and they outperformed the best results obtained with conventional statistical methods.

Yu and Chen [56] made a study to investigate the effectiveness of using NN for traffic prediction. A comparison between the results from the neural network approach and other approaches was provided. They concluded that the NN approach is an effective alternative to traditional techniques for traffic prediction.

Dougherty et al. [57] conducted a study to evaluate the effectiveness of NN in congestion recognition and short-term forecasting in traffic flow on an urban network. The results indicate that NN can provide a powerful method of analyzing, interpreting and predicting complex data sets.

The common types of ANN used in the literature are MLP, RBF and probabilistic NN. The most probable ANN type for our study is RBF, which is very useful for function approximation since in our study, we have several inputs (traffic volume of turning movements) and several outputs (optimum lane groups, cycle length and green times) and the main objective is to find an accurate function which relates the inputs to the expected outputs.

Numerical-learning-based algorithms are used for designing ANN models. The network has the capacity to adjust the parameters based on the training signals. The weights of the network are adjusted according to the set of input and outputs. The network is trained to estimate any nonlinear function with a desired accuracy [58].

Topology of ANN models depends on the data processing nature. In feedforward topology, nodes are arranged hierarchically in all layers of the model from input layer to output layer, including the hidden layer which provides the main computational power of the ANN model [59].

As ANN has the ability of self-learning and can approximate any nonlinear function, it is widely used in system dynamic modeling [60]. ANNs are also widely used for traffic flow prediction [61]. ANN models also have the ability of real-time implementation of traffic flow forecasting, so it is important in the application and development of advanced traffic control in Intelligent Transportation Systems (ITS). ANN prediction models are found to be more accurate compared to the traditional time-series prediction techniques [62]. These prediction models are mainly focused on freeway [63]–[65].

One of the common ANNs is Feed-Forward Neural Networks (FFNN). These networks are organized in layers, starting with the input layer and ending with the output layer. However, the main computational power is provided by the hidden layers located between the input and output layers [59].

Network training, the quantity and quality of the training data, network parameters like numbers of hidden layers, transfer function, number of epoch, number of neurons in hidden layers and the initial weights between the two neurons are influencing the performance of the ANN model. ANN models are effective in predicting traffic flow for short term and need long training time [66].

The literature on neural networks showed that Artificial intelligence (AI) techniques have been used for a variety of transportation research problems. They are reported to have good generalization capabilities for regression as well as classification problems and nonlinear relationships. In this study, neural networks will be used to develop a model that can be used to predict the optimal lane group for any combination of turning movement.

CHAPTER 3

DYNAMIC LANE GROUPING MODEL

This chapter describes the procedure of formulating the Dynamic Lane Grouping (DLG) model and the assumptions used in developing the model. MATLAB environment was used to develop the DLG model. The evaluation of DLG strategy was conducted in four stages which are: evaluation of DLG at one approach of the intersection, evaluation of DLG at all approaches of the intersection, model verification and then finding a quick method/s to predict the optimum lane group combinations at all approaches.

3.1 Model Formulation

A MATLAB model which was developed by the author and other researchers under a project (IN131009) in KFUPM [67] was adopted to be used in this study. Few assumptions were considered in building the DLG model as follows:

- **The applied phasing scheme at the intersection is the geographical phasing scheme** in which each phase is allocated for all movements (left, right and through) of one approach at the same time as shown in Figure 3-1. This is the only phasing scheme allowed in the study area.

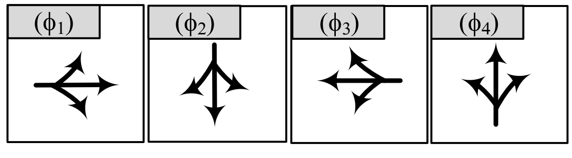


Figure 3-1 Geographical phasing scheme

- **The cycle length is optimized for each volume data set**. The cycle length, which results in the minimum intersection delay for a specific demand, was selected as the optimal cycle length for this demand.
- **Protected left turns**. Only protected left turns are considered, as these are the only legal left turns in the study area.
- **The principle of equal saturation flow ratio is used for shared lanes**. According to this principle, the traffic demand is distributed between the lanes serving the same movement in a way to keep the volume to saturation flow ratios for these lanes nearly equal to each other.

In this study, the DLG model was developed to achieve efficient intersection operation under a large variation in demand during the day. The objective function of the DLG optimization model is to minimize the average intersection delay per vehicle. To estimate the average intersection delay per vehicle, the proposed methodology by the Highway Capacity Manual was used. The average control delay per vehicle for a given lane is given by Equation (3-1).

$$d_{i,k} = d_{1,i,k}(PF) + d_{2,i,k} + d_{3,i,k} \tag{3-1}$$

where:

d : control delay per vehicle (sec);

$\boldsymbol{d_{1,i,k}}$: uniform control delay, assuming uniform arrivals for lane *k* at approach *i* (sec);

PF : progression adjustment factor, assumed to be 1;

$d_{2,i,k}$: average delay per vehicle due to random arrivals for lane k at approach i, which is called incremental delay (sec);

$d_{3,i,k}$: average delay per vehicle due to initial queue at the start of the analysis time period for lane k at approach i (sec).

The average delay for lane k at approach i due to uniform arrivals is estimated using Equation (3-2). The progression adjustment factor PF is assumed as 1 since we are considering isolated intersection only.

$$d_{1,i,k} = \frac{0.5C\left(1 - \frac{g_i}{C}\right)^2}{1 - \left[\min\left(1, x_{i,k}\right) . \ \frac{g_i}{C}\right]} \tag{3-2}$$

where:

C : cycle length (sec);

g_i : effective green time for lane group (sec);

$x_{i,k}$: total lane volume-to-capacity ratio (v) for lane k, where $c_{i,k} = S_{i,k}\left(\frac{g_i}{C}\right)$.

The incremental delay d_2 is estimated following Equation (3-3):

$$d_{2,i,k} = 900T\left(\left(x_{i,k} - 1\right) + \sqrt{\left(x_{i,k} - 1\right)^2 + \frac{8k_f I x_{i,k}}{c_{i,k}T}}\right) \tag{3-3}$$

where:

T : duration of analysis period (h);

k_f : incremental delay factor;

I : upstream filtering/metering adjustment factor;

$c_{i,k}$: lane capacity (veh/h).

Using Equation (3-1), the average delay per approach per lane $d_{i,k}$ can be estimated. Then, the average approach delay D_a is calculated through Equation (3-4).

$$D_a = \frac{\left(\sum_{k=1}^{K} d_{i,k} V_{i,k}\right)}{\left(\sum_{k=1}^{K} V_{i,k}\right)} \tag{3.4}$$

where K_i is the total number of lanes at approach i.

Since the model was developed for isolated signalized intersections, the value of the upstream filtering-metering adjustment factor (*I*) is assumed as 1.0, while the value of the incremental delay factor (***k***) is assumed as 0.5 since the signal operation is not actuated as recommended by HCM (2010) [68]. For simplification, it is assumed that there is no initial queue delay from the previous analysis period, which means that d_3 is 0 for all lanes. The effective green time for each phase was calculated using time budget concept in which the distribution of the effective green time is based on the critical volume to saturation flow ratio for each phase.

The DLG model was developed to accommodate all types of signalized intersections with any number of approaches and lanes. It is assumed that the number of approaching lanes K_i and the number of exit lanes are equal. A binary function was defined to identify the permitted movements "j" from lane "k" at approach "i" as follows:

$$\alpha_{i,j,k} = \left\{\begin{matrix} 0 & \text{turning movement } j \text{ from approach } i \text{ using lane } k \text{ is not allowed} \\ 1 & \text{turning movement } j \text{ from approach } i \text{ using lane } k \text{ is allowed} \end{matrix}\right\}$$

where:

i**:** *i*ntersection approach. i=1, 2, 3, 4, respectively, representing eastbound approach, southbound approach, westbound approach and northbound approach.

k**:** approach lanes, k=1, 2, 3….. N^i_A (numbered from offside to curbside lanes).

j**:** turning movements at the intersection, j=1, 2, 3, respectively, representing left-turn movement, through movement and right-turn movement.

The model was developed to find the optimum lane group for a specific demand following the flowchart shown in Figure 3-2.

The demand variation for each approach was considered by changing the left turn demand and the demand of the through movement independently while keeping the overall approach demand unchanged based on the following logic:

Given approach demand $V_i = V_{i,LT} + V_{i,TH} + V_{i,RT}$
For each $V_{i,LT} = 0.1V_i$ *to* $0.7V_i$
For each $V_{i,TH} = 0.1V_i$ *to* $(0.8V_i - V_{i,LT})$
$V_{i,RT} = V_i - V_{i,LT} - V_{i,TH}$

The saturation flow of a turning lane is defined by Equation (3-2) [69]:

$$S_{i,k} = \frac{\bar{S}_{i,k}}{1+1.5\sum_{j=1}^{j=3}\left(\frac{f_{i,k,j}}{r_{i,k,j}}\right)} \qquad (3\text{-}5)$$

where:

$S_{i,k}$: Saturation flow rate of lane k at approach i.

$\bar{S}_{i,k}$: Saturation flow rate for through movement (assumed to be 1900 veh/hr)

$r_{i,j,k}$: Turning radius for movement j (= ∞ for straight-ahead movement).

$f_{i,j,k}$: Flow factor, defined as the proportion of traffic movement *j* from lane *k* at approach *i* as shown in Equation (3-3). The flow factor equal 1 when no shared lane is involved.

$$f_{i,j,k} = \frac{V_{\ i,j,k}}{\sum_{j=1}^{j=3} V_{\ i,j,k}} \qquad (3\text{-}6)$$

where $V_{\ i,j,k}$ is the flow rate for movement *j* from arm *i* via lane *k*.

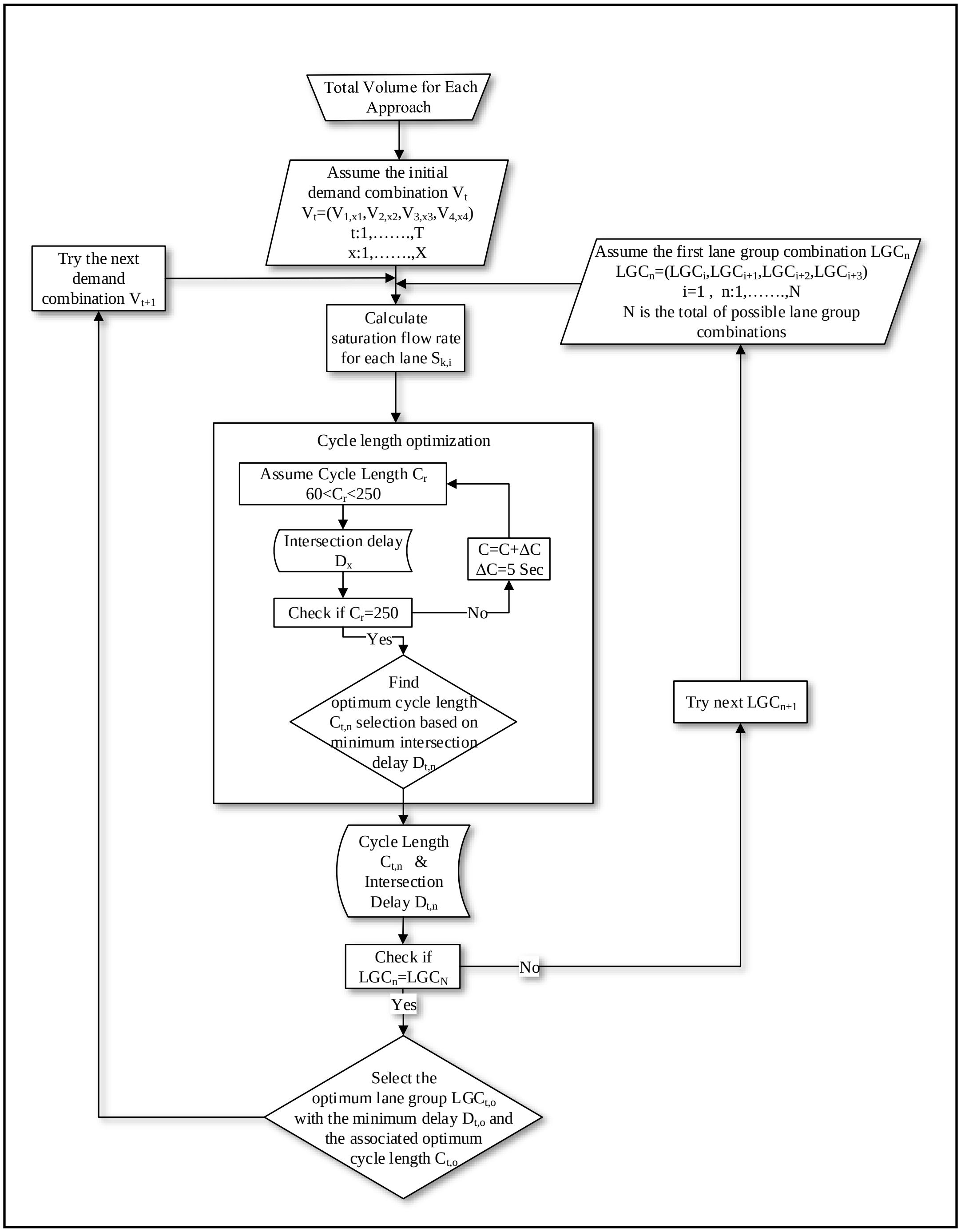


Figure 3-2 DLG Model Flowchart [67]

According to the Highway Capacity Manual (HCM) 2010 [68], the minimum cycle length acceptable to serve the pedestrians is 60 sec with no limitations on the maximum cycle length, which is suggested to be selected by the local jurisdiction. In this study, the minimum and maximum cycle lengths are assumed to be 60 sec and 250 sec, respectively. Using an increment of 5 sec, the cycle length, which results in the minimum intersection delay for a specific demand combination using a specific lane group, is selected as the optimized cycle length for this demand combination and lane group. Furthermore, the lane group, which results in the minimum intersection delay, is selected as the optimal lane group.

3.2 Study Intersection

The developed DLG model was tested on an intersection in Dhahran city, Saudi Arabia to find the optimum lane group for any possible percentage of turning movements. The chosen site is controlled by a pre-timed signal with negligible pedestrian activity and located where Abu-Obaida Street intersects with Prince Faisal Street. The intersection consists of four approaches, the east-west approaches are with four lanes and the north-south approaches are with three lanes as shown in Figure 3-3.

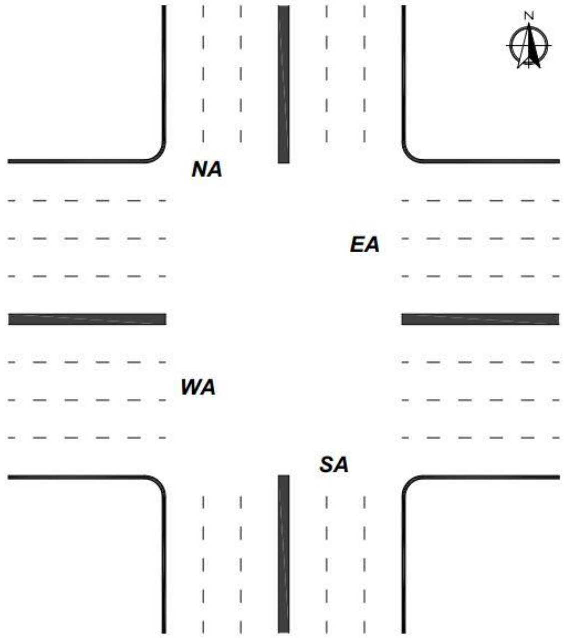


Figure 3-3 Intersection Layout

Traffic data collection for the turning movements was conducted at the intersection for AM peak hour, afternoon peak hour and evening peak hour during a typical weekday. Table 3-1 represents the turning traffic volumes at each approach during the three peak periods.

Table 3-1 Turning Traffic Volumes and Signal Timing Parameters [67]

	Observed vehicle demand (vehicle/hr.)												
	West approach			North approach			East approach			South approach			
Period	V_L	V_R	∑approach	V_L	V_R	∑approach	V_L	V_R	∑approach	V_L	V_R	∑approach	Intersection Volume
Morning peak 6:30-7:30	841	118	1628	160	278	474	11	90	1462	42	18	80	3644
Afternoon peak 12.00-13.00	850	9	1388	414	157	630	470	42	1412	352	152	611	4041
Evening peak 16:00-17:00	703	371	2199	329	250	669	661	155	1921	270	177	525	5314

* L: Left turn traffic R: Right turn traffic

Shared lanes are only permitted in the outer lanes. From a large number of possible lane groups' combinations, only 10 LGCs for 4-lane approaches and 6 LGCs for 3-lane approaches are practical and considered as shown in Figure 3-4.

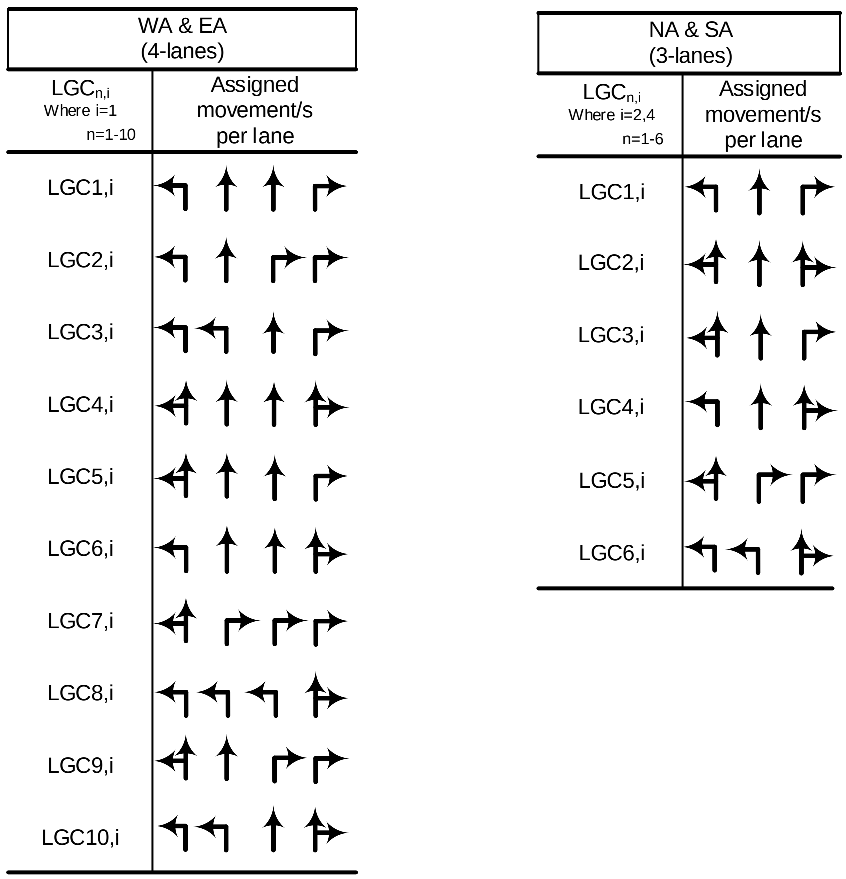


Figure 3-4 Lane Groups' Combinations Considered in DLG Model [67]

3.3 Evaluation of DLG Strategy at One Approach Only

A study was conducted by the author and other reserachers [70] to apply DLG at one approach only Before applying it at all approaches, which needs long computational and execution time. The eastbound approach (approach #1) was chosen to be the targeted approach for this stage. It was assumed that the other three approaches have fixed lane groups and fixed demands all the time. The vehicle demands observed during the morning peak (Table 3-1) were selected for the analysis. The fixed lane allocations and demands for the three other approaches are as follows:

$$\boldsymbol{\alpha_2 = Movement}\ \begin{array}{c c} & \begin{array}{ccc} \boldsymbol{k=1} & \boldsymbol{2} & \boldsymbol{3} \end{array} \\ \begin{array}{c} \boldsymbol{LT} \\ \boldsymbol{TH} \\ \boldsymbol{RT} \end{array} & \begin{pmatrix} \mathbf{1} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{1} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{1} \end{pmatrix} \end{array},$$

$$\boldsymbol{\alpha_3 = Movement}\ \begin{array}{c c} & \begin{array}{cccc} \boldsymbol{k=1} & \boldsymbol{2} & \boldsymbol{3} & \boldsymbol{4} \end{array} \\ \begin{array}{c} \boldsymbol{LT} \\ \boldsymbol{TH} \\ \boldsymbol{RT} \end{array} & \begin{pmatrix} \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{1} & \mathbf{1} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} \end{pmatrix} \end{array},$$

$$\boldsymbol{\alpha_4 = Movement}\ \begin{array}{c c} & \begin{array}{ccc} \boldsymbol{k=1} & \boldsymbol{2} & \boldsymbol{3} \end{array} \\ \begin{array}{c} \boldsymbol{LT} \\ \boldsymbol{TH} \\ \boldsymbol{RT} \end{array} & \begin{pmatrix} \mathbf{1} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{1} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{1} \end{pmatrix} \end{array},$$

$$\boldsymbol{V_i = Approach\ i}\ \begin{array}{c c} & \boldsymbol{Movement} \\ & \begin{array}{ccc} \boldsymbol{LT} & \boldsymbol{TH} & \boldsymbol{RT} \end{array} \\ \begin{array}{c} \mathbf{2} \\ \mathbf{3} \\ \mathbf{4} \end{array} & \begin{pmatrix} \mathbf{160} & \mathbf{36} & \mathbf{278} \\ \mathbf{11} & \mathbf{1361} & \mathbf{90} \\ \mathbf{42} & \mathbf{20} & \mathbf{18} \end{pmatrix} \end{array},$$

Using the assumed fixed vehicle demands for the NA, EA and SA and the generated demand combinations for the targeted approach (WA), the developed model was used to identify the optimal lane group combination (LGC_o) for the WA and to estimate the resulting average intersection delay. At a specific demand combination of the WA, the lane group combination that resulted in the minimum average intersection delay, was selected as the optimal lane group combination (LGC_o).

Figure 3-5 shows 3D surface representations of the estimated average intersection delays for DLG and Fixed Lane Grouping (FLG) at different demand combinations of the WA.

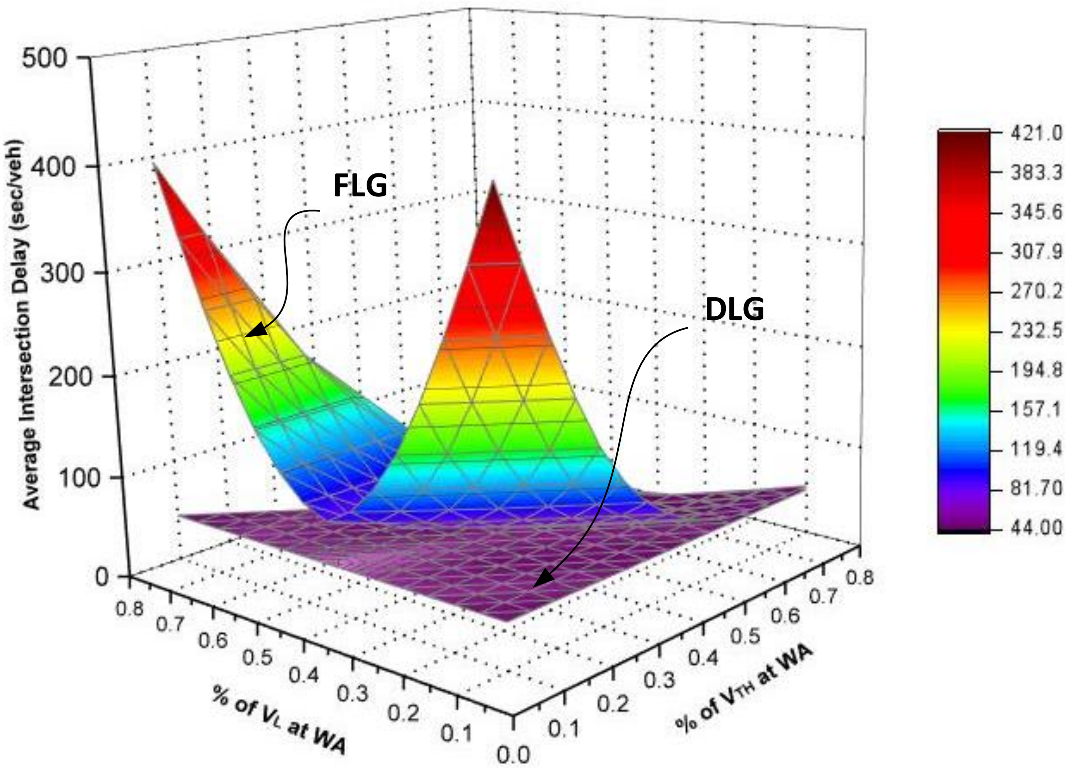


Figure 3-5: Comparison between estimated minimum average intersection delay resulting from DLG and the estimated average intersection delay resulting from FLG with optimized cycle length[70]

It is clear that there is a significant reduction in average intersection delay, which increases as the proportions of turning traffic at WA become larger.

3.4 Evaluation of DLG Strategy at All approaches

Based on the results of the previous section, it was decided to extend the DLG strategy to cover all the approaches of the intersection. This study [71] was conducted as part of the same project (IN131009) with the cooperation of other researchers at KFUPM. The same assumptions and equations were followed to build the DLG model for all intersection approaches.

Figure 3-6 represents a comparison between the estimated average intersection delays of DLG and FLG strategies. The x-axis and the y-axis present the proportions of LT volume from the total approach volume at the WA and EA, respectively.

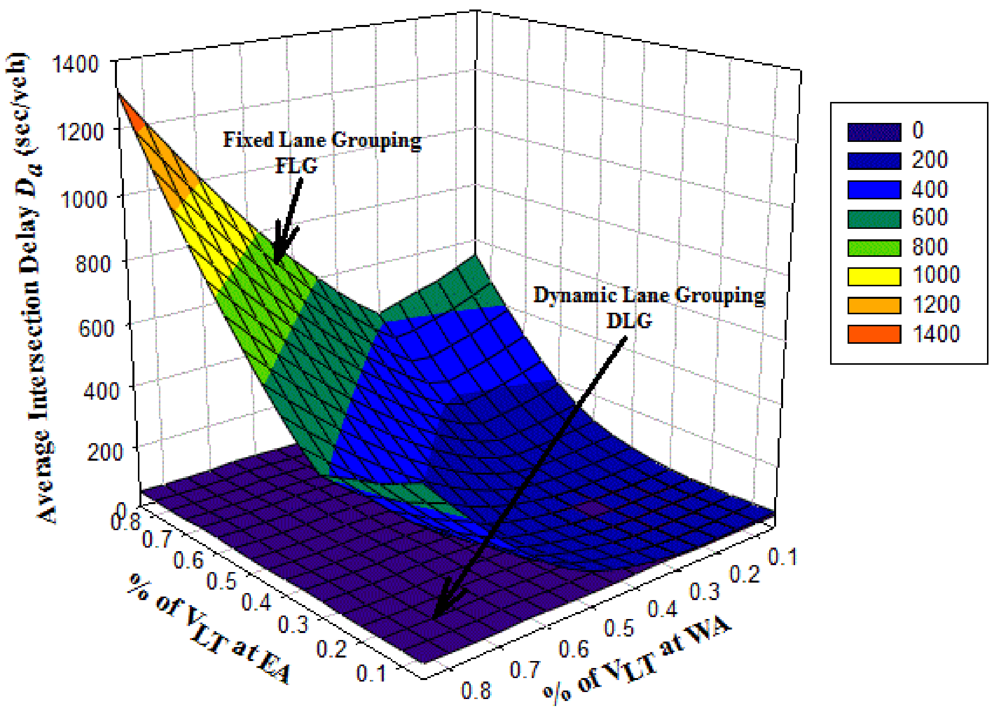


Figure 3-6 Comparison between estimated average intersection delays of DLG and FLG strategies using optimized signal timings [71]

It is clear that DLG yields to significant reductions in *average intersection delay* compared to FLG. These reductions increase as the proportions of LT movement increase where it reaches up to 96%. The analysis revealed significant improvements in intersection performance with reductions in average intersection delays that reached up to 82%. The developed model optimizes space and time resources simultaneously, pushing it to the highest possible performance. Furthermore, the proposed model produced rational and reasonable LGC_o that provides an optimum space distribution between traffic movements based on their relative demand.

3.5 Model Verification

It can be observed from Figure 3-4 that 10 LGCs for 4-lane approaches and 6 LGCs for 3-lane approaches were considered in this study. Hence, the total number of lane group combinations for each volume turning movement combination is 3600 (10*6*10*6), out of which the model will choose the LGC_o based on the minimum average intersection delay. Because of that, it was difficult or impossible to verify the developed MATLAB model manually. To overcome this problem, a Mixed Integer Programming (MIP) model was developed using the LINGO package to find the optimal lane group combinations at an isolated signalized intersection for any given volume using an objective function of minimizing intersection delay. Mixed Integer Programming (MIP) is one type of mathematical programming programs in which some variables are integer and the others are continuous. This mathematical programming has been used widely in optimization problems related to transportation engineering. This model was developed using the same equations and constraints used in developing the MATLAB model. The objective function and constraints of the MIP model are shown below.

VT_A= Total approach volume at approach A;

$AD_{A,i,j,k,z}$= Average approach delay at approach A using configuration i at approach 1, configuration j at approach 2, configuration k at approach 3 and configuration z at approach 4, is calculated using Equations (3-1), (3-2), (3-3) and (3-4) in section 3.1;

$$B_{i,j,k,z} = \left\{ \begin{array}{l} 1 \quad if \quad configurations\ i,j,k\ and\ z\ are\ used\ at\ approach\ 1,2,3\ and\ 4, respectively. \\ \qquad\qquad\qquad\qquad i,k = 1,2,\dots 10\ and\ j,z = 1,2,\dots 6 \\ \\ 0 \quad Otherwise \end{array} \right\};$$

$$MIN = \frac{\left(\sum_{i=1}^{10}\sum_{j=1}^{6}\sum_{k=1}^{10}\sum_{z=1}^{6} B_{i,j,k,z} \sum_{A=1}^{4} VT_A * AD_{A,i,j,k,z}\right)}{\sum_{A=1}^{4} VT_A};$$

Subject to;

$$\sum_{i=1}^{10}\sum_{j=1}^{6}\sum_{k=1}^{10}\sum_{z=1}^{6} B_{i,j,k,z} = 1;$$

$$B_{i,j,k,z} = 0,1 \qquad i,k = 1,2,\dots 10$$
$$j,z = 1,2,\dots 6$$

A comparison was conducted between both models by running the models on hypothetical turning movement volumes. It was found that both models are giving exactly the same results.

3.6 Comparison with Microscopic Simulation

In this section, the developed model was verified by comparing its optimum lane group combination with that of SimTraffic microsimulation tool, which is being used widely by local engineers and offices in the study area [72]. For comparison purposes, we assumed that the lane group combination will be dynamic at one approach (west approach) only while the other approaches will have fixed lane group combinations and fixed traffic volumes. Three movement volume combinations were chosen randomly at west approach. Each movement volume combination was simulated 10 times (one simulation for each lane group combination) using SimTraffic and the resulting intersection delay for each simulation was reported. The lane group combination with the minimum intersection delay was chosen as the optimum lane group combination for that case of movement volume combination and then compared with that resulting from the developed model as shown in Table 3-2.

Table 3-2 Comparison Between SimTraffic and Developed Model

Case 1:	$V_L = 138$	$V_{TH} = 971$	$V_R = 279$
$LGC_{1,n}$	**Intersection delay (sec/veh) (SimTraffic)**	**Optimum LGC at WA (SimTraffic)**	**Optimum LGC at WA (Developed Model)**
1	84.6	4	4
2	317.3		
3	309.6		
4	66.3		
5	66.5		
6	82.5		
7	428.5		
8	603.8		
9	103.6		
10	175.6		
Case 2:	$V_L = 347$	$V_{TH} = 347$	$V_R = 694$
$LGC_{1,n}$	**Intersection delay (sec/veh) (SimTraffic)**	**Optimum LGC at WA (SimTraffic)**	**Optimum LGC at WA (Developed Model)**
1	189.2	2	2
2	70.3		
3	207.1		
4	303.0		
5	186.7		
6	323.5		

7	128.9		
8	468.6		
9	70.70		
10	246.4		
Case 3:	$V_L = 132$	$V_{TH} = 832$	$V_R = 418$
$LGC_{1,n}$	**Intersection delay (sec/veh) (SimTraffic)**	**Optimum LGC at WA (SimTraffic)**	**Optimum LGC at WA (Developed Model)**
1	95.5	5	5
2	202.3		
3	195.1		
4	118.5		
5	92.1		
6	99.9		
7	303.3		
8	638.8		
9	109.7		
10	183.9		

It can be observed from Table 3-2 that the optimum lane group combination resulting from SimTraffic is the same as that resulting from the developed model although the delay amounts are different.

3.7 Developing a Quick Method to Predict the Optimum Lane Group Combinations at All Approaches

The objective of this section is to develop a new method, which can be used to find the optimal lane group combination for each approach quickly. To achieve this objective, a huge data set was generated using the developed model as shown in the following sub-section.

3.7.1 Data analysis and results

The model was executed as explained in Figure 3.2 in the afternoon peak hour volumes and then in the evening peak hour volumes since these peak periods have the highest intersection volumes compared to the morning peak period. A third run was executed in a hypothetical peak hour volume, in which the highest observed traffic volume (evening peak period) was assigned to the west and north approaches while the opposing approaches (i.e. east and south) were assigned 30% and 50% of the highest observed volume at these approaches, respectively. This ensures large practical variations in traffic volumes between the opposing approaches with the same number of lanes. Table 3-3 summarizes the approach and intersection volume for the hypothetical peak hour. For each run, the percentage of turning volumes were systematically changed at a rate of 10% at each approach. The rate of 10% was based on the fact that this increment will result in more than 600,000 cases of turning volume combinations for each trial, which require one month of parallel execution by high performance computers which are using K-20 Graphics Processing Unit (GPU) cluster. This execution time was considered as the maximum practical time that can be economically accepted in this research.

Table 3-3 Approach Volumes for the Hypothetical Peak Hour

Approach	Volume (veh/hr)
West Approach	2200
East Approach	700
North Approach	700
South Approach	350
Intersection volume	3750

Table 3-4 shows the relationship between different increments and total number of turning movement combinations, which indicates that the increment of 10% is logical in terms of the number of combinations and execution time. Increments less than 10% will result in a huge number of combinations and very long execution time. On the other hand, the increments larger than 10% will result in a small number of combinations, which is not adequate for study purposes.

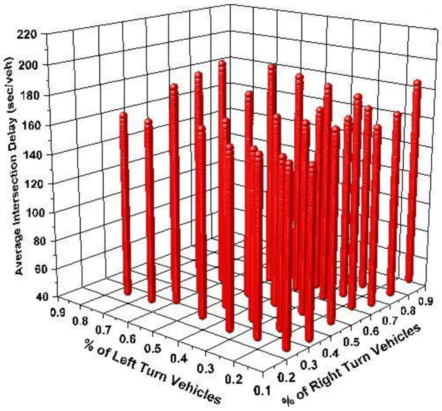
Table 3-4 Total Number of Turning Movement Combinations for Different Increments

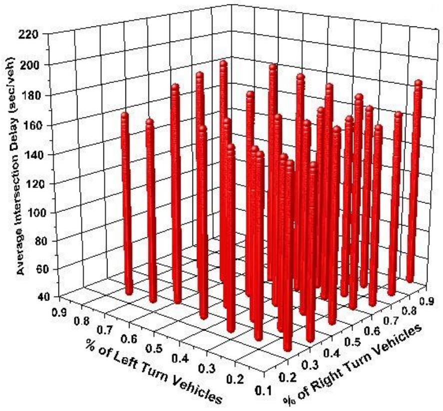
Increment	Number of turning movement combinations*
0.01	3.8133×10^{13}
0.05	68574961
0.10	614656
0.15	50625
0.20	10000

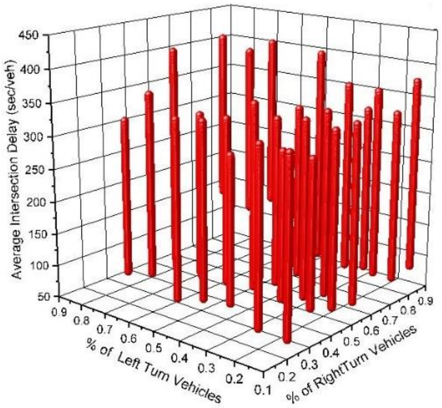
*turning movement combinations mean all possible combinations of turning movements at all approaches

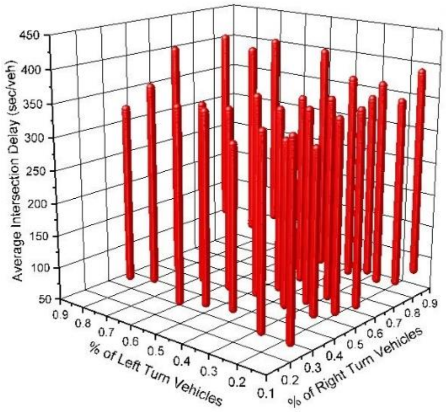
For each turning movement combination, the model found the optimum lane group combinations for all approaches at the intersection based on the minimum intersection delay. Table 3-5 and Table 3-6 show the 3D scatter plots of the average intersection delay at the 614,656 different percentages of left and right turning movements at east-west approaches and north-south approaches, respectively, for the three peak hour volumes considered in this study.

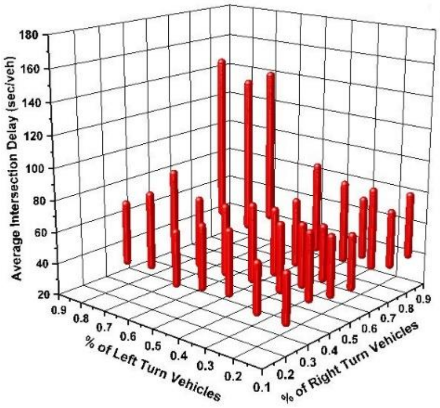
Table 3-5 3D Scatter Plots of the Intersection Delay (4-Lane Approach)

<table>
<tr><th>West Approach</th><th>East Approach</th></tr>
<tr><td colspan="2">Afternoon peak hour volumes</td></tr>
<tr><td>


</td><td>


</td></tr>
<tr><td colspan="2">Evening peak hour volumes</td></tr>
<tr><td>


</td><td>


</td></tr>
<tr><td colspan="2">Hypothetical peak hour volumes</td></tr>
<tr><td>


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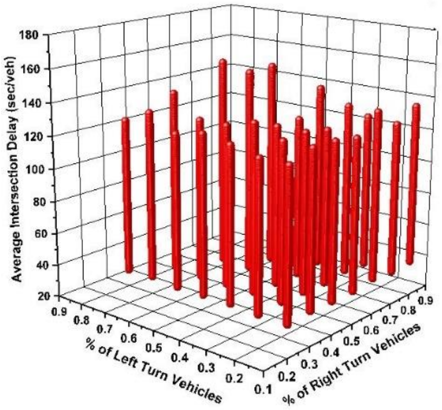
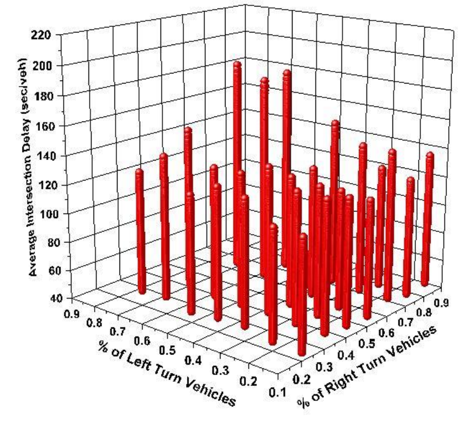


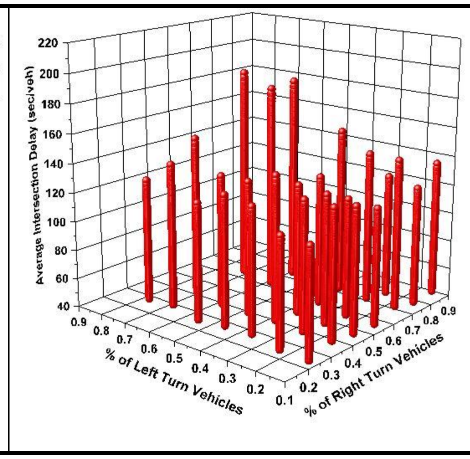
</td></tr>
</table>

Table 3-6 3D Scatter Plots of the Intersection Delay (3-Lane Approach)

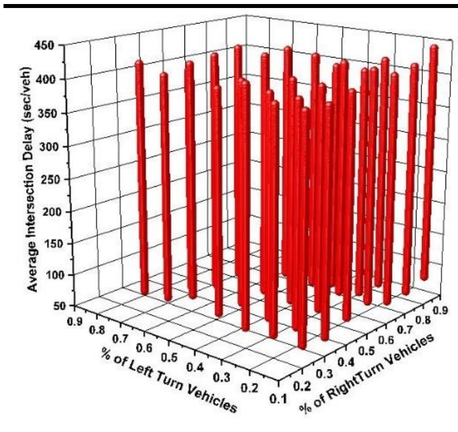
North Approach	South Approach

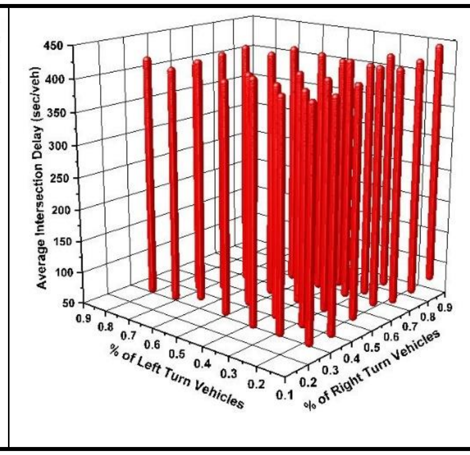
Afternoon peak hour volumes



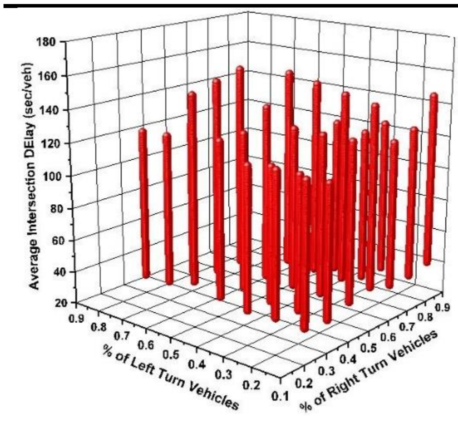


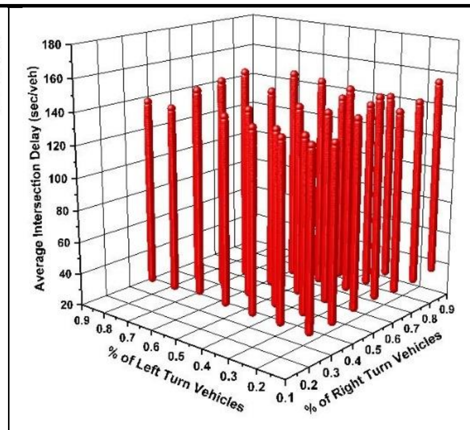
Evening peak hour volumes





Hypothetical peak hour volumes

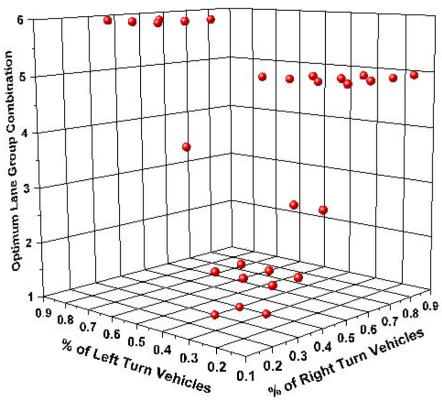
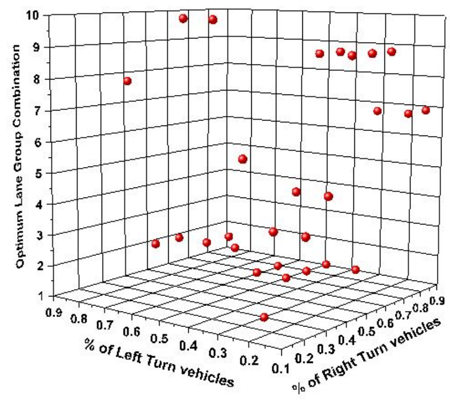




It can be observed from Table 3-5 and Table 3-6 that at each percentage of turning movements, there are many stacked points above each other (i.e. column of points), which represent different delay values at the same percentage of turning movements at the given studied approach, but with different percentages of turning volumes at the three remaining approaches. Consequently, the different values of delay for the same percentage of turning movements at the given approach were due to the changes in turning movements at the other approaches, while maintaining the same left and right turning volumes at the studied approach.

Table 3-7 shows the LGC_o number (as given in Figure 3-4) for all possible percentages of turning movements at 3-lane approach and 4-lane approach for the three peak periods considered (i.e. 614,656 × 3 data points). Although the values of delay at 3-lane approaches and 4-lane approaches are significantly different when the three peak periods were compared to each other, the optimum lane group for each approach geometry (3-lane approaches and 4-lane approaches) is represented by only one figure during the three peak hours. On the other hand, it is clear that many stacked points of intersection delay represent each percentage of turning movement while it is represented by only one point of LGC_o. This gives an indication that the changes in the percentages of turning movements at other approaches will not affect the LGC_o for a specific turning combination at the specific approach under investigation. Hence, a quick method was identified to predict the LGC_o at 3-lane approaches and 4-lane approaches based only on the percentage of turning movements at the targeted approach regardless of the percentages of turning volumes at the other approaches.

Table 3-7 3D Scatter Plots of the Optimum Lane Group Combination (for the 3 Peak Periods)

3-lane approaches	4-lane approaches
	

Each point in the above 3D scatter plots represents the LGC_o for the specific right and left turning percentages for the 614,656 cases of each peak period (i.e. 614,656*3 data points).

Based on the finding that the optimum lane group depends on the percentage of the turning volumes at the targeted approach regardless of the volume of the other approaches, the model was executed again, assuming that the turning movement variations will occur at one 3-lane approach only while fixing the percentages of the turning movements at the other approaches. The same procedure was repeated for a 4-lane approach. As the model was executed by considering the demand variation at one approach only, an increment of 0.01 was used instead of 0.1 to consider all possible turning movement percentages. This increment will result in 1891 combinations of turning movements (instead of 614,656), which need three minutes of execution time using high performance computers. Figure 3-7 and Figure 3-8 show the boundary area for each optimum lane group for all possible turning movement combinations at 3-lane approaches and 4-lane approaches, respectively.

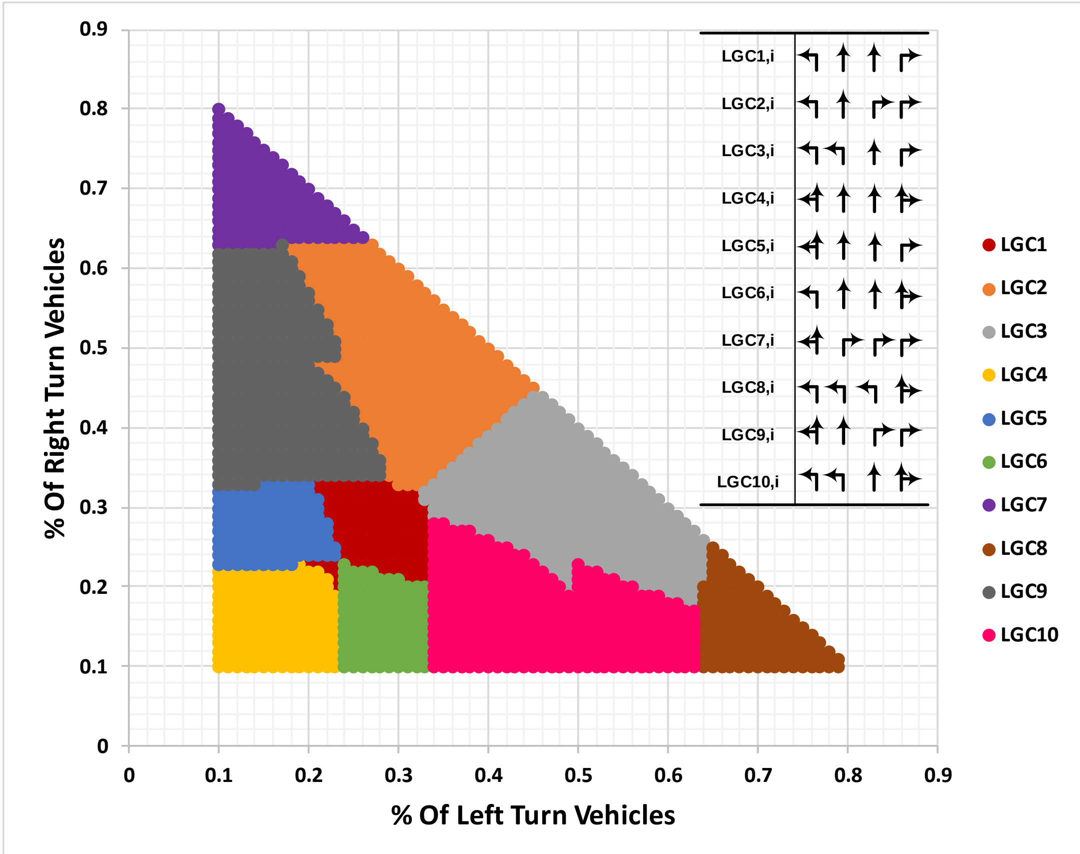


Figure 3-7 Lane Group Combinations Boundaries (4-Lane Approaches)

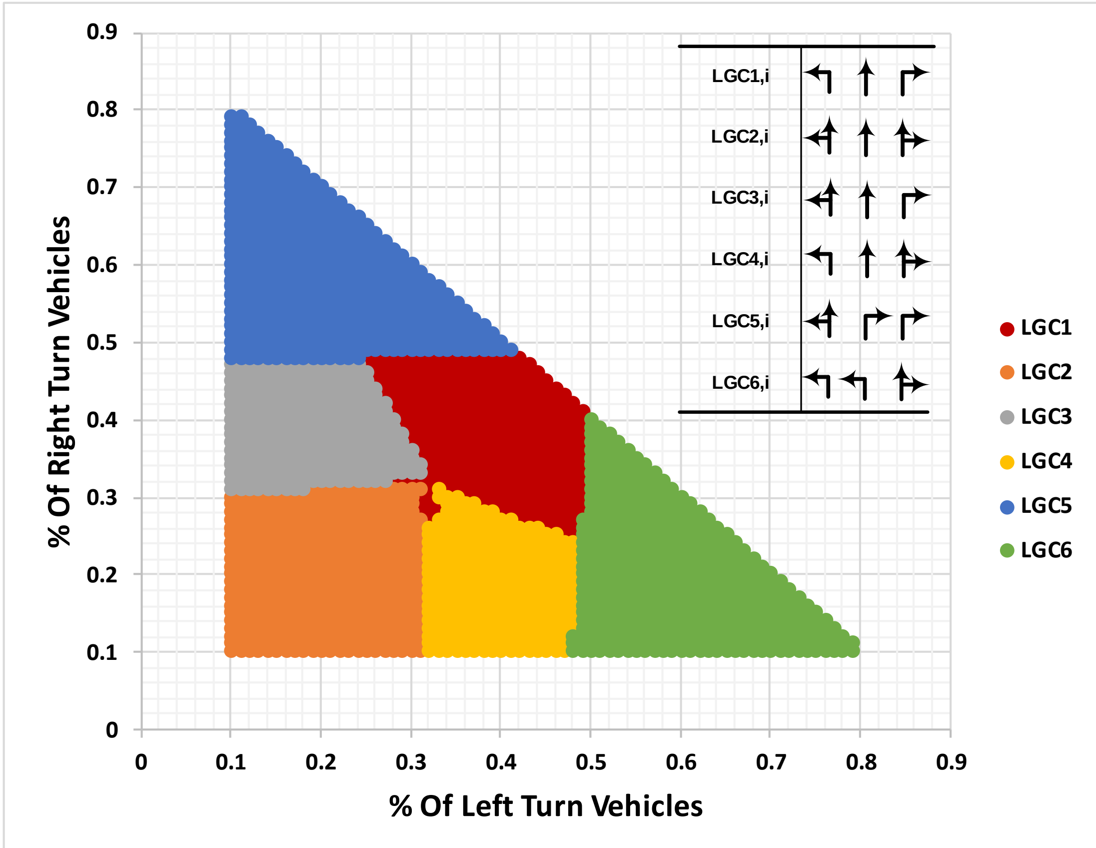


Figure 3-8 Lane Group Combinations Boundaries (3-Lane Approaches)

The results digested in Figure 3-7 and Figure 3-8 are encouraging to look for logical rules to select the optimum lane group on the basis of turning movement, especially for 3-lane approaches. These figures can be used to generate lookup tables, which can be uploaded to the signal controller and then can be used to predict the optimum lane group directly after detecting/predicting the percentages of turning movements. This finding represents a plausible quick method to predict the optimum lane group in the field instantaneously using the percentage of turning movements at the approach without conducting massive calculations.

It can be observed from Figure 3-7 and Figure 3-8 that there are some irregularities near the boundaries between the areas of optimum lane groups. Hence, we made a further investigation at the boundaries by choosing a random sample of turning movement percentages which are very close to these boundaries and then we compared the delays resulting from the optimum lane groups sharing the same boundary at each turning movement percentage. We found that at the boundaries, there is no significant difference in delays resulting from the selection of the optimum lane groups on either side of the boundaries.

3.8 Evaluation of Applying Pre-signal with DLG

Pre-signalization is a proposed technique that can be used to facilitate the process of applying the DLG strategy. The idea of the pre-signals is to give priority to a specific movement or mode before reaching the main signal. For the purpose of DLG application, pre-signals can help in reducing the drivers' weaving maneuver by giving the green time for each lane separately so that the driver will be able to choose the appropriate lane without any conflict with the traffic on the other lanes.

3.8.1 Case study

The objective of this case study is to make a comparison between the average approach delay at 4-lane approach with fixed lane grouping (FLG) and the average approach delay for the same approach after applying both the DLG technique and pre-signals. The Highway Capacity Manual (HCM) delay equations were used to find the average approach delay for all cases. It is assumed that each lane will be controlled by its own pre-signal as shown in Figure 3-9. Only green and red indications will be applied at each lane as there is no need for yellow indication. Hence, the green time for each lane will be 25% of the cycle length (g/c = 0.25). The saturation flow rate is 1900 veh/h/lane as through movement is the only turning movement available at the pre-signal.

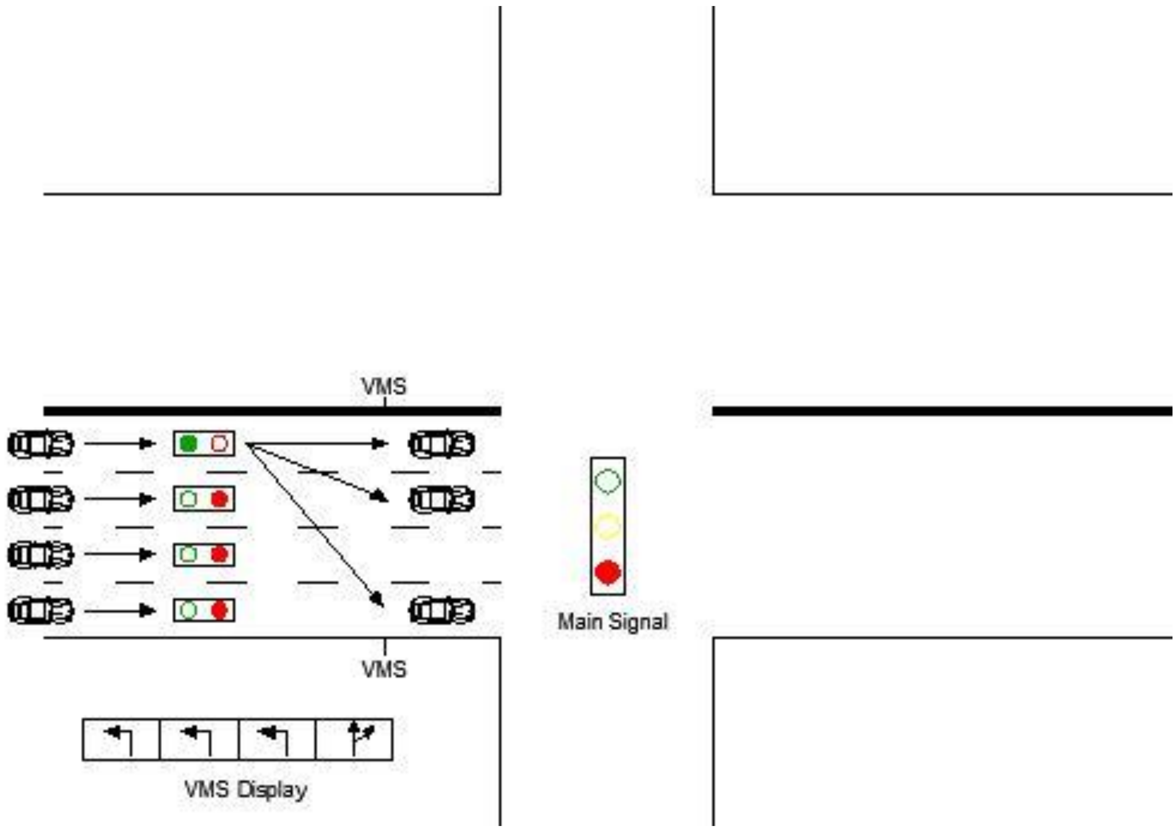


Figure 3-9: Pre-Signal Layout

The afternoon peak hour volume at the west approach was chosen for comparison purposes and to optimize the cycle length for pre-signal. It is assumed that the approach volume will be distributed equally over all lanes (347 veh/hr/lane). We assumed that the cycle length will range from 20 seconds (5 seconds of green for each lane) to 80 seconds (20 seconds of green for each lane) using an increment of 20 seconds. The cycle length, which resulted in the minimum average delay, was chosen as the optimal cycle length. Table 3-8 shows the resulting average approach delay for different cycle lengths.

Table 3-8: Cycle Length Optimization for Pre-signal

Cycle Length (sec)	Approach Delay (sec/veh)
20	16.94
30	20.39
40	23.83
50	27.27
60	30.71
70	34.15
80	37.59

It can be observed from the previous table that the optimum cycle length for the pre-signal is 20 seconds with 5 seconds of green for each lane.

3.8.2 Comparison between fixed lane grouping (FLG) and dynamic lane grouping (DLG) *without pre-signal*

The MATLAB model was executed assuming that the turning movement variations will occur at the west approach only using an increment of 0.01 to consider all possible turning movement percentages. For each combination of turning movement, two values of average approach delay were recorded, one when applying FLG and the other when applying DLG.

Figure 3-10 shows 3D surface representations of the estimated average approach delays for DLG without pre-signal and FLG at different demand combinations.

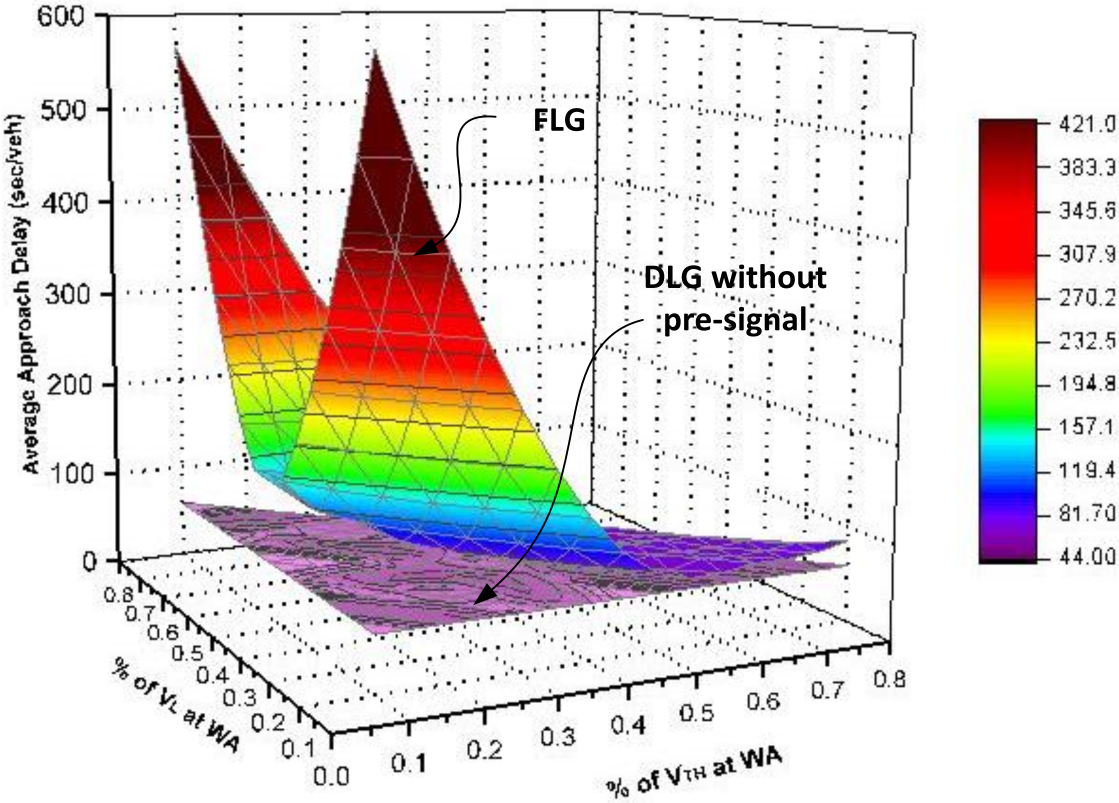


Figure 3-10 3D surface representations of the estimated average approach delays for DLG without pre-signal and FLG at different demand combinations.

It is clear that there is a significant reduction in average approach delay after applying the DLG technique.

3.8.3 Comparison between fixed lane grouping (FLG) and dynamic lane grouping (DLG) *with pre-signal*

The average approach delay resulting from the pre-signal using the optimal cycle length (16.94 sec/veh for a cycle length of 20 sec) was added to the DLG average approach delay for all turning movement combinations and then compared with average approach delay for FLG.

Figure 3-11 shows 3D surface representations of the estimated average approach delays for DLG with pre-signal and FLG at different demand combinations.

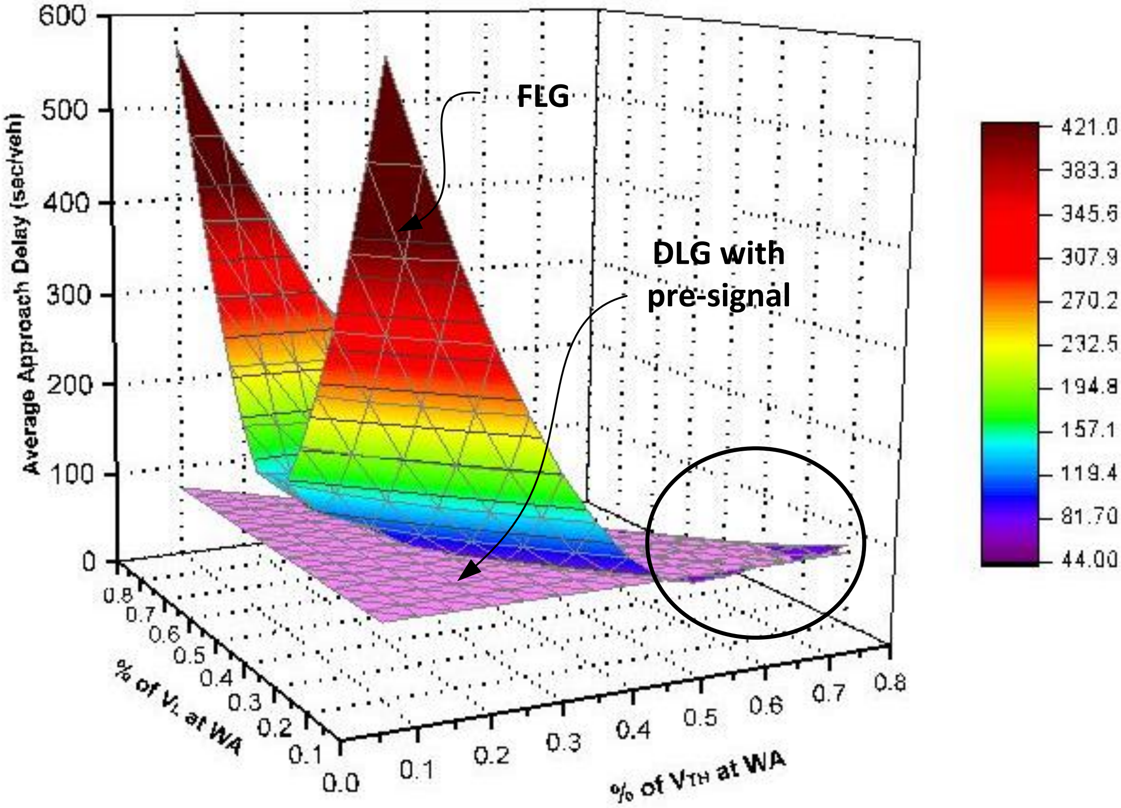


Figure 3-11 3D surface representations of the estimated average approach delays for DLG with pre-signal and FLG at different demand combinations.

It can be observed from the previous figure that for almost all turning movement percentages, the DLG with pre-signal is better than FLG in terms of average approach delay except for some points, which represent 30% of all points (circled in the figure) where the delay of DLG with pre-signal is higher than that for FLG. The maximum difference in delay between DLG with pre-signal and FLG for these points was found to be 20 seconds while the minimum difference was found to be 0.23 seconds, which gave an indication that applying pre-signals will not affect significantly the superiority of DLG.

3.8.4 Site selection criteria for testing DLG

As mentioned in the previous sections, DLG model was developed to enhance the operation performance of intersections which are suffering from a significant changes in turning movement demand during the day. For instance, when at least one of any intersection approaches experiences heavy left-turn demands and relatively low through demand in the morning, while in the afternoon the opposite situation happens, this can give an indication that this intersection will be a good candidate for testing DLG. On the other hand, the selected intersection for testing should has no safety issues and with low pedestrian activities. Furthermore, the candidate intersection should be used mostly by commuters.

3.9 Determining Traffic Volume on the Middle Shared Lanes

It is a very lengthy procedure to find the traffic volumes on the shared lanes using the principle of equal volume to saturation flow rate ratios. In this study, we came up with a procedure which can help in finding the traffic volume on shared lanes for any number of approach lanes in a shorter time. The principle of equalization of saturation flow ratio was utilized to achieve this objective. According to this principle, the traffic demand is distributed between the lanes serving the same movement in a way to keep the volume to saturation flow ratios for these lanes nearly equal to each other. For clarification purposes, we considered a case of 5-lane approach with two shared lanes in the middle as shown in Figure 3-12.

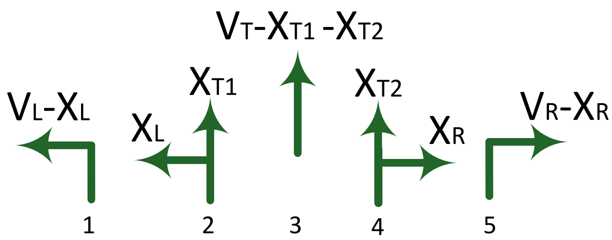


Figure 3-12: Lane Group Combination Considered for Shared Lane Volume Computation

where:

V_L : left traffic volume
V_R : right traffic volume
V_T : through traffic volume
X_R : shared right traffic volume
X_L : shared left traffic volume
X_T : shared through traffic volume

The objective is to find the values of X_L, X_R and X_T. Equation (3-2) was utilized to find the saturation flow for all lanes. As each two lanes beside each other shared the same movement, they will have the same volume to saturation flow ratio (assumed to be equal to α) based on the principle of equal saturation flow ratio. The saturation flow rates for all lanes were calculated as follows:

For lane 1:

$$S_1 = \frac{15200}{9}\ veh/hr$$

For lane 2:

$$S_2 = \frac{1900}{1 + 1.5\left(\frac{X_L}{12(X_L + X_{T1})}\right)}$$

For lane 3:

$$S_3 = 1900\ veh/hr\ \ (exclusive\ through\ lane)$$

For lane 4:

$$S_4 = \frac{1900}{1 + 1.5\left(\frac{X_R}{10(X_R + X_{T2})}\right)}$$

For lane 5:

$$S_5 = \frac{38000}{23}\ veh/hr$$

By equalizing the volume to saturation flow ratio for the adjacent lanes, the following equations were obtained:

$$0 = 1900\alpha - X_{T1} - \frac{9}{8}X_L$$

$$0 = 1900\alpha - X_{T2} - \frac{23}{20}X_R$$

$$V_L = \frac{15200}{9}\alpha + X_L$$

$$V_R = \frac{38000}{23}\alpha + X_R$$

$$V_T = 1900\alpha + X_{T1} + X_{T2}$$

The above equations can be written in a matrix form *M*. *X*=*V*, where:

$$M = \begin{bmatrix} \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{\frac{15200}{9}} \\ \mathbf{0} & \mathbf{1} & \mathbf{1} & \mathbf{0} & \mathbf{1900} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{\frac{38000}{23}} \\ -\mathbf{\frac{9}{8}} & -\mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{1900} \\ \mathbf{0} & \mathbf{0} & -\mathbf{1} & -\mathbf{\frac{23}{20}} & \mathbf{1900} \end{bmatrix},$$

$$X = \begin{bmatrix} \boldsymbol{X_L} \\ \boldsymbol{X_{T1}} \\ \boldsymbol{X_{T2}} \\ \boldsymbol{X_R} \\ \boldsymbol{\alpha} \end{bmatrix},$$

$$V = \begin{bmatrix} \boldsymbol{V_L} \\ \boldsymbol{V_T} \\ \boldsymbol{V_R} \\ \boldsymbol{0} \\ \boldsymbol{0} \end{bmatrix},$$

The values of X can be obtained by multiplying the inverse of M by V as shown below:

$$X = M^{-1}.V$$

In this case, $M^{-1} = \begin{bmatrix} 0.8 & -0.1778 & -0.2044 & -0.1778 & -0.1778 \\ -0.675 & 0.40 & 0.46 & -0.60 & 0.40 \\ 0.45 & 0.40 & -0.69 & 0.40 & -0.60 \\ -0.196 & -0.174 & 0.80 & -0.174 & -0.174 \\ 0.0012 & 0.00011 & 0.00012 & 0.00011 & 0.00011 \end{bmatrix}$

The following equations can be used to calculate $X_{L,}$ X_R and X_T :

$X_L = 0.80 * V_L - 0.1778 * V_T - 0.2044 * V_R$

$X_{T1} = -0.675 * V_L + 0.408 * V_T + 0.46 * V_R$

$X_{T2} = 0.45 * V_L + 0.40 * V_T - 0.69 * V_R$

$X_R = -0.196 * V_L - 0.174 * V_T + 0.80 * V_R$

It can be observed from the previous calculations that the shared lane volumes can now be calculated easily by finding the matrix that represents the targeted case. The previous example provided a clear vision about dealing with the shared lanes for any number of approach lanes. This clarification can encourage the future researchers to consider any number of approach lanes with the existence of the middle shared lanes.

3.10 Environmental Benefits of Applying DLG

Besides its impact in reducing in average delay per vehicle at signalized intersections, applying DLG also has positive environmental impacts as it has a significant role in decreasing fuel consumption and gas emissions. The environmental effects of space and time optimization was determined by comparing some measures of effectiveness MOEs such as fuel consumption and gas emissions resulted from optimizing signal timing only with those resulted from optimizing time and space using DLG over the peak hours shown in Table 3-1. SYNCHRO which is a macroscopic simulation tool was used to measure these MOEs for both cases. All comparison results are shown in Table 3-9.

Table 3-9 MOEs Comparison

MOE	Optimizing signal timing only	Optimizing time and space together	% Reduction
Morning peak hour (Total intersection volume = 3644veh/hr)			
Fuel Used (l/hr)	1783	1014	43.1%
CO emissions (g/hr)	33170	18870	43.1%
NOx emissions (g/hr)	6400	3640	43.1%
VOE emissions (g/hr)	7650	4350	43.1%
Afternoon peak hour (Total intersection volume = 4041 veh/hr)			
Fuel Used (l/hr)	1463	364	75.1%
CO emissions (g/hr)	27210	6742	75.2%
NOx emissions (g/hr)	5250	1312	75.0%

VOE emissions (g/hr)	6280	1562	75.1%
Evening peak hour (Total intersection volume = 5314 veh/hr)			
Fuel Used (l/hr)	3992	1423	64.4%
CO emissions (g/hr)	74250	26460	64.4%
NOx emissions (g/hr)	14330	5110	64.3%
VOE emissions (g/hr)	17120	6100	64.4%

It can be observed from the previous table that optimizing space and time using DLG model decreased the fuel consumption and gas emissions considerably over the three peak hours.

3.11 Economic Benefits of Applying DLG

The value of travel time is a critical foctor in evaluating the benefits of transportation investment. Reduction of delay in passenger of freight transportation is a major purpose of investment. The objective of this section is to convert the reduction in delay after applying DLG to monetary value so that the dicision maker will has a better understanding for the effect of applying DLG. The procedure of U.S department of transportion DOT [73] is followed to achieve this objective. Table 3-10 represents the proportions of hourly income for different categories used by DOT to convert delay to a monetary value

Table 3-10 Recommended Values of Travel Time Savings (per person-hour as a percentage of total earnings)[73]

Category	Surface Modes	Air and High-Speed Rail Travel
Local Travel-		
Personal	50%	---
Business	100%	---
Intercity Travel-		
Personal	70%	70%
Business	100%	100%

The values in the table above represent the ratios of the Value of Travel Time Saving (VTTS) to hourly incomes. For instance, for personal surface mode, the VTTS each reduced hour of delay equal to 50% of the hourly income for the driver.

In our study, all of the traffic are local travel and we assumed that 50% of traffic is for personal purposes and 50% is for business purposes. Based on that assumption, the ratios of the Value of Travel Time Saving (VTTS) to hourly incomes were taken as the average of personal and business proportions which is 75%. According to latest Household Expenditure and Income Survey of Saudi Arabia [74], the average monthly income in Saudi Arabia is SAR10723 which is equivelant to SAR45 per hour.

In order to evaluate the economic benifets of DLG, the model was executed over the three peak hours on a typical weekday shown in table Table 3-1 and then the reduction in delay was calculated and converted to a monatory value as shown in Table 3-11.

Table 3-11 Travel Time Saving in SAR After Applying DLG

Peak hour	Total intersection traffic volume (Veh/hr)	Average intersection Delay (DLG) (sec/veh)	Average intersection Delay (FLG) with optimal cycle length (sec/veh)	Reduction in total intersection delay (hr)	Travel time Saving (SAR)
Morning	3404	36.37	282.22	232.46	10461
Afternoon	4281	70.09	436.77	436.04	19622
Evening	5314	260.40	279.33	27.94	1257
Total					**31340**

To explaine the calculation procedure for travel time saving, the morning peak hour was chosen for sample calculation. It can be observed from Table 3-11 that the reduction in total intersection delay after applying DLG during the peak hour is 232.46 hours. To find the travel time saving for the morning peak hour, the total intersection delay (232.46 hrs) was multiplied by the hourly income for the driver (45SAR) and then multiplied by the ratio of the Value of Travel Time Saving (VTTS) to hourly income (75%).

It can be observed from Table 3-11 that the total monetary saving after applying DLG at one intersection for three hours only is SAR31340. These results give strong indications that applying DLG ~~at all intersections~~ in the urban network can save a lot of money.

CHAPTER 4

FEEDFORWARD NEURAL NETWORK MODEL

Neural networks can be considered as one of the most popular artificial intelligence (AI) techniques. Researchers try to incorporate the human intelligence into computing machines to enhance their ability in performing complex tasks. In this chapter, feedforward neural network was used to develop an ANN model which can be used to predict the optimum lane group combination at intersection approaches using turning movement volumes. On the other hand, this chapter explains the way of optimizing the topology of the ANN model to ensure a reasonable accuracy.

4.1 Concept of Feedforward Neural Network

Artificial intelligence (AI) techniques have been used for a variety of transportation research problems. They are reported to have good generalization capabilities for regression as well as classification problems [75]. One of the most popular AI techniques is neural networks. Researchers try to incorporate the human intelligence into computing machines to enhance their ability in performing complex tasks. Artificial neurons have similarities with the biological neurons like learning from experience, generalization from previous experiences and application to new data.

The feedforward neural network structure was inspired by the structure of a real brain. It consists of a number of layers that contain neurons like processing units. Every unit in a layer is connected with all the units in the previous layer. The weights on these connections encode the knowledge of a network. The feedforward neural network has the ability to predict the outputs of any unknown function accurately. It consists of three layers which are input layer, hidden layer and output layer. Each layer comprises of a number of units called neurons. The input layer has number of neurons similar to the number of input variables, and the neurons in the output layer are equal to the number of output variables. The number of neurons in the hidden layer are equal to the number of training samples. The input neurons forward the input vector to all the neurons in the hidden layer.

Figure 4.1 represents an example of a 2-layered network with, from left to right: an output layer with 2 units and a hidden layer with 4 units, respectively. The network has 3 input units.

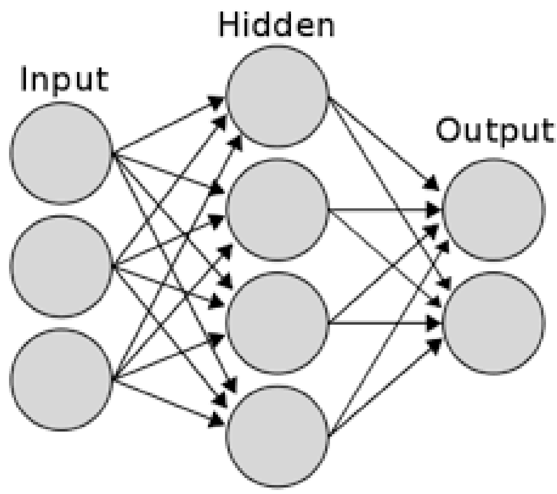


Figure 4.1: Example of 2-Layered Network

4.2 Model Development

Many studies have been conducted to determine the topology of the neural network [76]–[78]. It was concluded that the precise topology required to solve a specific problem cannot be determined.

This is a critical problem in the neural-network field, since a network that is too small or too large for the problem at hand may produce poor results. Hence, some general rules of thumb regarding the topology of the network are very common nowadays. At least one hidden layer should be used. The number of nodes used in each intermediate layer are typically between the number of nodes used for the input and output layers [78]. Ultimately, the only method that can be confidently used to determine the appropriate number of layers in a network for a given problem is trial and error [79].

Trial and error principle for determining the optimum network topology involves many steps, which start with a small number of hidden layers and then build it larger until it reaches the required accuracy without causing overfitting; such algorithms are known as constructive algorithms.

The relationship between the demand variation and the optimum lane group combination was found to be nonlinear and uncertain, which led to the use of ANN to solve this problem. The ANN model was developed in order to predict the optimum lane groups' combination for a typical isolated signalized intersection based on any traffic demand within the domain of the model using the MATLAB environment. In this problem, the input layer consists of 12 inputs (3 movement volumes at each approach) and 4 outputs which represent the optimum lane group combination at each approach. As mentioned in Chapter 3, three peak hour volumes were considered in this study and the model was executed three times (one run for each peak hour). For each run, the percentage of turning volumes were systematically changed at a rate of 10% at each approach. The rate of 10% was based on the fact that this increment will result in 614,656 cases of turning volume combinations with a total number of 614,656×3 cases, which represent a huge data set. A sample of

50,000 turning volume combinations was chosen randomly from each peak hour to train and test the ANN model. Each sample consists of 50,000 turning volume combinations with a total of 150,000 turning volume combinations, out of which 75% was used for training and the remaining combinations were used for testing. The optimum topology (number of layers, number of neurons per layer and the type of transfer function) was selected by trial and error procedure. The first step was to choose a simple topology with minimum hidden layers and less number of neurons and then increase the number of neurons and number of hidden layers until reaching a point at which the ANN model can predict the optimum lane group combinations with reasonable accuracy.

4.3 Performance Evaluation

As mentioned in section 4.2, three samples were selected randomly to train and test the ANN model. 75% of the turning volume combinations were chosen for training the ANN model and the remaining combinations were kept for testing. The following characteristics were chosen to build the ANN model:

Model type: Feed forward back propagation (FFBP)

Training algorithm: Levenberg-Marquardt

Calculation Environment: MATLAB

Data Division: Random

Problem Type: Prediction

Selecting the topology: Trial and error

Performance Measure: Accuracy

Trial and error algorithm [79] was followed to develop the optimum neural network topology. The idea of this algorithm is to start with a basic structure of NN using one hidden layer and then increase the number of neurons and hidden layers until reaching the optimum topology which can predict the outputs with reasonable accuracy without causing overfitting. The optimum topology for the ANN model was found to be 3 hidden layers with 14 neurons in each layer with an average accuracy of 92%.

CHAPTER 5

VMS EVALUATION THROUGH DRIVERS' INTERVIEWS

Variable Message Signs (VMS), as one of the widely used intelligent transportation systems (ITS), especially in urban areas, can significantly support the implementation of Dynamic Lane Grouping (DLG) by providing drivers with real-time information about the existing lane group configuration while approaching signalized intersections. However, the location and timing of the displayed information on lane group configuration need to be carefully studied. It is important to provide drivers with sufficient time to make decisions and smoothly select the proper lane based on their desired movement without causing confusion or misunderstanding, which might lead to sudden lane changing maneuvers. Based on the above, interviews were conducted to explore the drivers' response to the information about the existing configuration when disseminated via VMS.

5.1 Survey Design

It was decided to collect disaggregated data through a questionnaire interview survey in Khobar-Dhahran Metropolitan areas, Saudi Arabia, because it is more effective in capturing travelers' behavior [80]. The questionnaire encompassed most of the variables considered important in the literature, which are age, occupation, education level and driving experience [40], [50]. Sudman [81] suggested that the sample should be large enough to encompass a minimum of 100 elements in each group of major category of the population and 30 elements in other categories . The major category considered in this study is the age group since it is found in the literature to be the most significant variable that may affect the drivers' response to VMS. The sample data was monitored and analyzed on a daily basis to ensure that at least 100 responses for each major category are collected The age groups and the number of responses in each age group are given in Table 5-1.

Table 5-1 Statistics of Major Category

Age group (years)	Number of responses
17-24	100
>24-40	103
>40	101

The main objective of the questionnaire interview survey was to evaluate the understanding of the regular commuters with VMS messages about DLG. For interview purposes, two videos (each video was developed for different configurations as shown in Figure 5-1 and Figure 5-2), which emulated the traffic movement at one approach of the studied intersection, were developed. In each video, three variable message signs about the existing configuration were placed before the intersection. The first sign was placed 270 m from the intersection, which represents enough distance to provide an adequate perception reaction time [82]. The second sign was placed 180 m from the intersection and the last sign was placed 90 m from the intersection.

These videos were introduced to 304 interviewees who were chosen randomly in the study area and then the interviewer asked them six questions about VMS signs (three questions for each video) to know if the drivers understood the signs or not. Moreover, the interviewees were asked about the characteristics that were found to be significant in the literature, such as age, education level, occupation and driving experience, as shown in Table 5-2.

Figure 5-1 Screen Shot from the First Video (First Configuration)

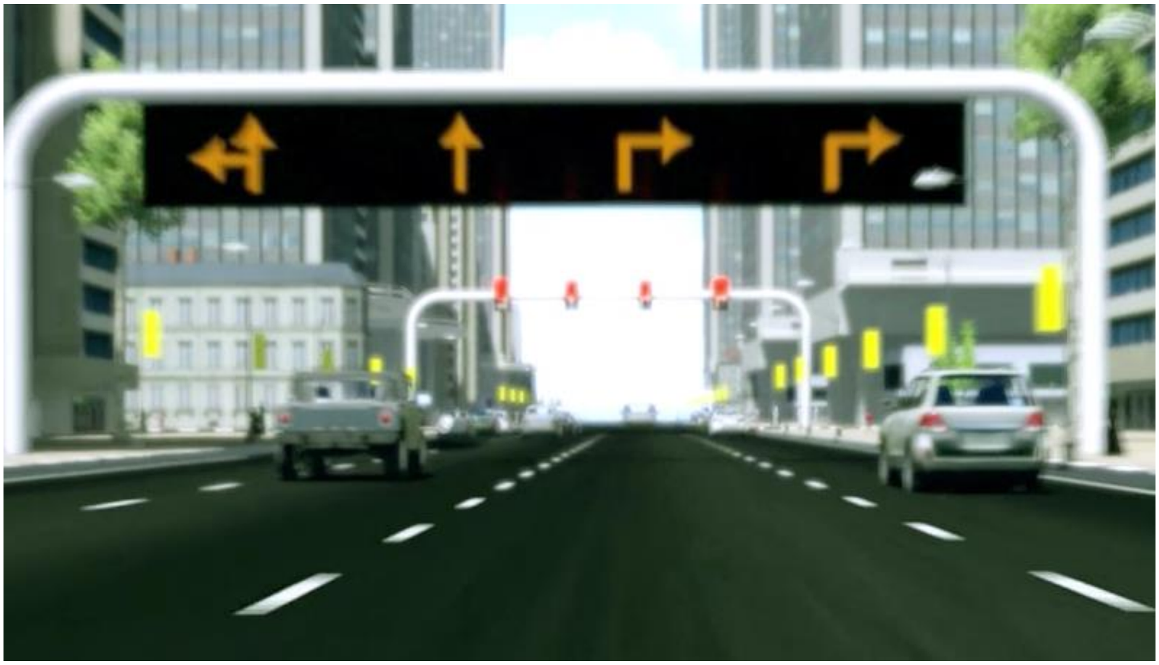


Figure 5-2 Screen Shot from the Second Video (Second Configuration)

5.2 Characteristics of the Interviewed Population

The questionnaire survey was designed to collect some information about the drivers' characteristics such as age, education level, occupation and driving experience. Table 5-2 represents the characteristics of the drivers considered in the survey and their options.

Table 5-2 The Considered Characteristics in the Questionnaire Survey

Driver characteristics	Options
Age group	17-24 years
	>24-40 years
	>40 years
Education level	High school or below
	Higher than High school
Occupation	Chauffeur
	Student
	Others
Driving experience	<5 years
	5-10 years
	>10 years

It can be shown from Table 5-2 that the occupation was divided into three sub-groups which are chauffeur, student and others. Chauffeurs were considered in this study as they represent a high percentage of drivers in the study area and they are from different countries with different backgrounds and cultures. On the other hand, students were considered as they differ from other drivers by some characteristics, such as aggressive behavior in driving, fast driving and reckless driving.

The distribution of the interviewed population over all options is shown in Figure 5-3, Figure 5-4, Figure 5-5 and Figure 5-6.

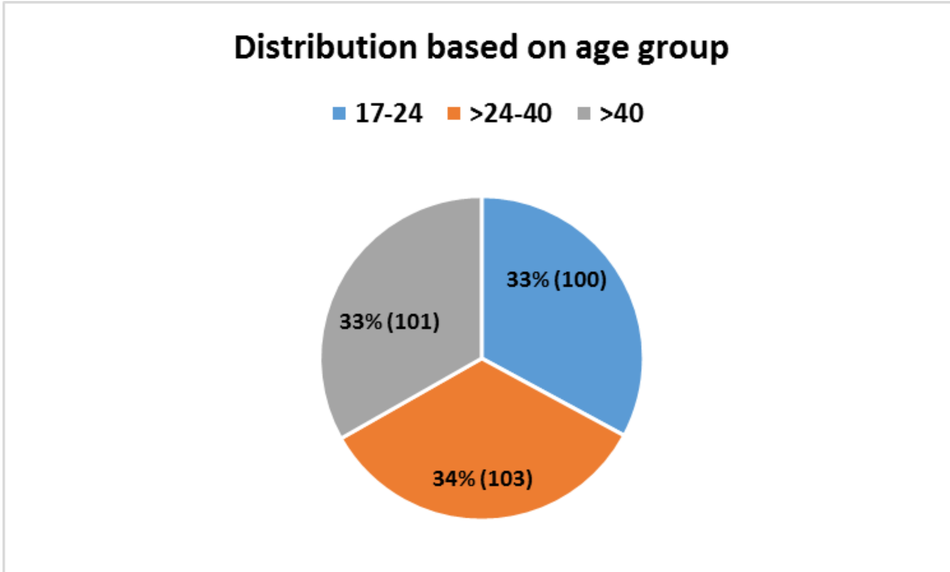


Figure 5-3 Distribution of Population Based on Age Group

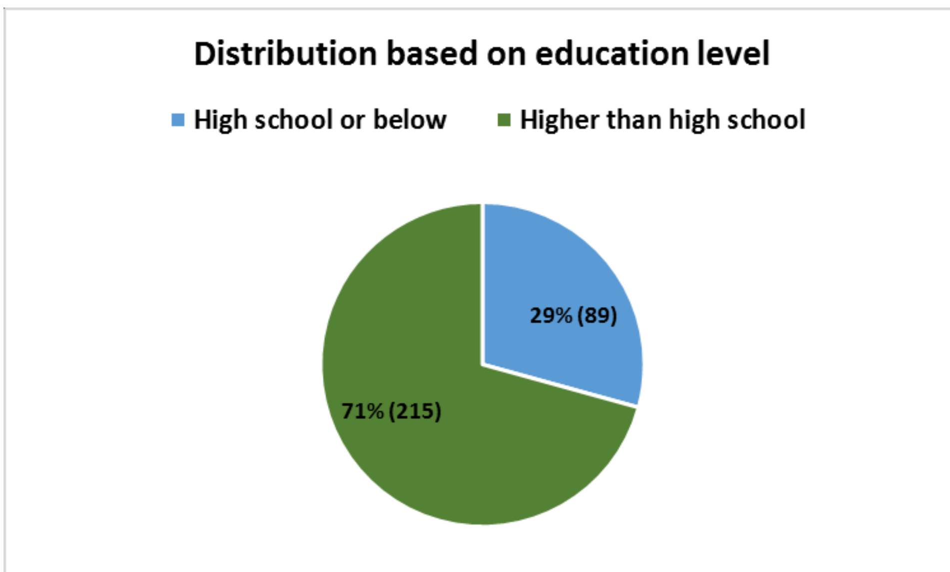


Figure 5-4 Distribution of Population Based on Education Level

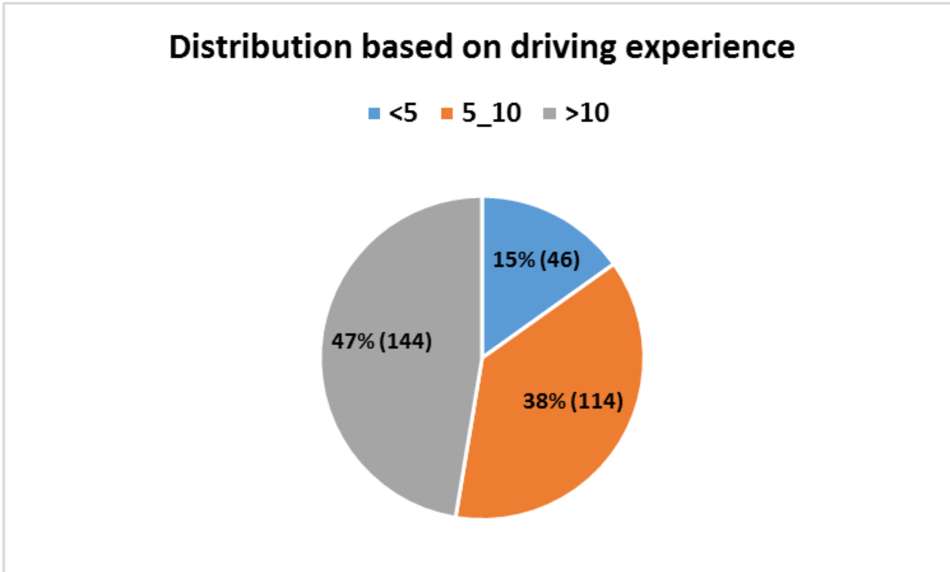


Figure 5-5 Distribution of Population Based on Driving Experience

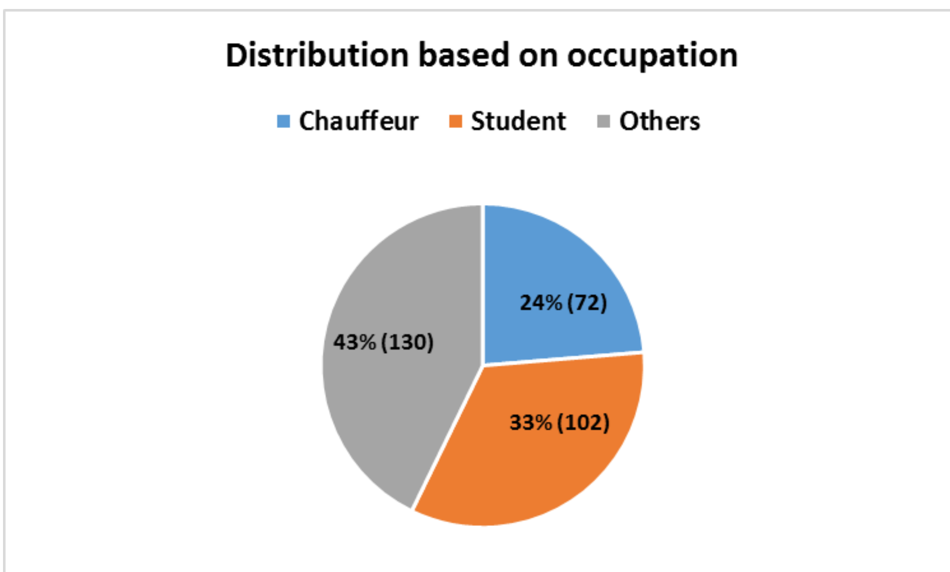


Figure 5-6 Distribution of Population Based on Occupation

It can be observed from the previous figures that the minimum requirement of 30 elements in each minor category was accommodated.

5.3 Statistical Analysis

The effect of drivers' characteristics such as age, occupation, driving experience and education level on their response to VMS was statistically tested at 95% confidence level using contingency analysis. Two options of the driver's response were considered, which are pass in understanding VMS or fail in understanding VMS. The driver who answered the six questions about the signs correctly was considered as a passed driver, otherwise, he was considered as a failed driver.

A hypothesis was set for the relationship between the drivers' characteristics and the response to VMS, as follows:

H_0 : the driver characteristic and response to VMS are independent

H_1 : the driver characteristic and response to VMS are not independent

The contingency analysis was done in three steps:

1. The observed frequency for each cell in the contingency table was recorded;
2. The expected frequency for each cell in the contingency table was calculated.
3. The chi-square statistic was calculated for each cell.

To find out which variable has the highest contribution to the relationship, the measured chi- square value was compared with the critical chi-square value at 95% confidence level. The null hypothesis will be rejected if the calculated chi-square value is greater than the critical value. Tables 5-3, 5-4, 5-5 and 5-6 represent the contingency analysis for each variable considered in the survey.

Table 5-3 Contingency Analysis Based on Age Group

	Observed Frequencies			
	Age group (years)			
	17-24	**>24-40**	**>40**	**Total**
Pass	72	59	68	**199**
Fail	28	44	33	**105**
Total	**100**	**103**	**101**	**304**
	Expected Frequencies			
	Age group (years)			
	17-24	**>24-40**	**>40**	**Total**
Pass	65.46	67.42	66.12	**199**
Fail	34.45	35.58	34.88	**105**
Total	**100**	**103**	**101**	**304**
	Chi-square test statistic			
	Age group (years)			
	17-24	**>24-40**	**>40**	$\sum$
Pass	0.65	1.05	0.05	**X^2 = 5.10**
Fail	1.21	1.99	0.10	

Table 5-4 Contingency Analysis Based on Occupation

	Observed Frequencies			
	Occupation			
	Chauffeur	**Student**	**Others**	**Total**
Pass	27	75	97	**199**
Fail	45	27	33	**105**
Total	**72**	**102**	**130**	**304**
	Expected Frequencies			
	Occupation			
	Chauffeur	**Student**	**Others**	**Total**
Pass	47.13	66.77	85.1	**199**
Fail	24.87	35.23	44.9	**105**
Total	**72**	**102**	**130**	**304**
	Chi-square statistic			
	Occupation			
	Chauffeur	**Student**	**Others**	$\sum$
Pass	8.6	1.0	1.66	**X^2 = 32.61**
Fail	16.3	1.9	3.15	

Table 5-5 Contingency Analysis Based on Driving Experience

	Observed Frequencies			
	Driving experience (years)			
	<5	**5-10**	**>10**	**Total**
Pass	32	72	95	**199**
Fail	14	42	49	**105**
Total	**46**	**114**	**144**	**304**
	Expected Frequencies			
	Driving experience (years)			
	<5	**5-10**	**>10**	**Total**
Pass	30.11	74.62	94.26	**199**
Fail	15.89	39.38	49.74	**105**
Total	**46**	**114**	**144**	**304**
	Chi-square statistic			
	Driving experience (years)			
	<5	**5-10**	**>10**	$\sum$
Pass	0.12	0.09	0.01	$X^2 = 0.60$
Fail	0.22	0.17	0.01	

Table 5-6 Contingency Analysis Based on Education Level

	Observed Frequencies		
	Education level		
	High School or Below	**Higher than High School**	**Total**
Pass	38	161	**199**
Fail	51	54	**105**
Total	**89**	**215**	**304**
	Expected Frequencies		
	Education level		
	High School or Below	**Higher than High School**	**Total**
Pass	58.26	140.74	**199**
Fail	30.74	74.26	**105**
Total	**89**	**215**	**304**
	Chi-square statistic		
	Education level		
	High School or Below	**Higher than High School**	∑
Pass	7.05	2.92	**X^2 = 28.80**
Fail	13.35	5.53	

It can be observed from the previous tables that the chi-square statistics for the age and driving experience as shown in Table 5-3 and Table 5-5, respectively, are less than the critical chi-square at 95% with 2 degrees of freedom (5.991). Hence, the null hypothesis cannot be rejected, which gave an indication that the age and driving experience have no effect on the response to VMS. On the other hand, the calculated chi-square values for the occupation and education level shown in Table 5-4 and Table 5-6 were found to be 32.61 and 28.80, respectively, which are very high compared to the chi-square value at 95% confidence level with 2 degrees of freedom for occupation (5.991) and 1 degree of freedom for education level (3.841). This means that there is a strong relationship between understanding of VMS on one hand and occupation and education level on the other hand. To explain these relationships clearly, the expected frequencies were compared with the observed frequencies for occupation and education level. It can be observed that the expected frequencies for the chauffeurs and high school or below education level persons who responded to VMS correctly, are more than the observed frequencies, while the expected frequencies and observed frequencies for other occupations and education levels are nearly equal. Hence, the chi-square statistics for the chauffeurs and high school or below education level persons are much higher than that for the others.

In conclusion, the chauffeurs and high school or below education level drivers responded wrongly to the messages related to dynamic lane grouping, which were displayed on VMS. Moreover, it was found that the number of failed low educated drivers is 55 and the total number of failed chauffeurs is 42 and all of them are low educated. This gave a strong indication that chauffeurs are the critical subcategory, who need excessive orientation before applying the new technique. Also, it gave an indication that the level of education is the most significant variable that affected the response to VMS disseminating information about DLG. More analysis was conducted for each configuration separately. It was found that the percentage of drivers who answered correctly the questions about the second configuration (as shown in Figure 5.2) are more than that of the first configuration, which represents a logical finding since the drivers in the study are not familiar with the configurations that will give a large number of lanes for a specific turning movement while giving only one lane for the other turning movements.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Signalized intersection is an important element of any road network. Its operations impact adversely the environment and safety and further affect significantly the performance of the whole road system. A considerable variability in traffic demand is expected at most signalized intersections in urban areas. Most of such intersections nowadays are prone to the phenomenon of tide traffic where different traffic movements at each approach (left, through and right) are fluctuating significantly with time. This phenomenon has a significant role in degrading the intersections performance and results in congestion along with excessive emissions of harmful gases. This study was conducted to investigate the effectiveness of applying dynamic lane assignment strategy, which is also known as dynamic lane grouping, to optimize signal timing plans. The concept of Dynamic Lane Grouping (DLG) has been introduced by many researchers to mitigate such operation problems. DLG is a technique that allows dynamic changing of lane utilization in response to the changes in the turning movement percentages at each approach. The applicability of dynamic lane grouping in real life practice is considered as a major concern of this new technique.

This study was conducted in three parts: evaluation of applying DLG, assessment of supportive techniques such as variable message signs and pre-signals and, finally, finding a quick method/s to predict the optimal lane group for any turning volume combination. More details about these parts are given in the proceeding sections.

6.1 Evaluation of Applying DLG

MATLAB environment was used to develop the DLG model, considering the following assumptions:

- The applied phasing scheme at the intersection is the geographical phasing scheme.
- The cycle length is optimized for each volume data set.
- Only protected left turns are considered, as these are the only legal left turns in the study area.
- The principle of equal saturation flow ratio is used for shared lanes.

The objective function of the DLG optimization model is to minimize the average intersection delay per vehicle. To estimate the average intersection delay per vehicle, the proposed methodology by the Highway Capacity Manual, which depends mainly on the cycle length, green time and saturation flow rate, was used. The DLG model was developed to accommodate all types of signalized intersections with any number of approaches and lanes. It is assumed that the number of approaching lanes and the number of exit lanes are equal. The demand variation for each approach at the intersection was considered by changing the left turn demand and the demand of the through movement independently while keeping the overall approach demand unchanged.

According to the highway capacity manual (HCM) 2010, the minimum cycle length acceptable to serve the pedestrians is 60 sec with no limitations on the maximum cycle length, which is suggested to be selected by the local jurisdiction. In this study, the minimum and maximum cycle lengths are assumed to be 60 sec and 250 sec, respectively. Using an increment of 5 sec, the cycle length, which results in the minimum intersection delay for a specific demand combination using a specific lane group, was selected as the optimized cycle length for this demand combination and lane group. Furthermore, the lane group, which resulted in the minimum intersection delay, was selected as the optimal lane group.

The developed model was tested on an intersection in Dhahran city, Saudi Arabia to find the optimum lane group for any possible percentage of turning movements. The intersection consists of four approaches, the east-west approaches are with four lanes and the north-south approaches are with three lanes. Traffic data collection for the turning movements was conducted at the intersection for AM peak hour, afternoon peak hour and evening peak hour during a typical weekday. A comparison was conducted between the average intersection delay for DLG and Fixed Lane Grouping (FLG) at different demand combinations. It was observed that applying DLG yields a significant reduction in average intersection delay compared to FLG. Moreover, it was observed that applying FLG strategy leads to unreliable operation since possible fluctuations in the turning traffic demand proportions lead to oversaturation condition and extremely long delays. In contrast, DLG provides a stable performance where the volume-to-capacity ratios are kept under 1.0.

It was difficult to verify the developed MATLAB model manually due to the huge number of lane group combinations for each turning movement combination. To overcome this problem, a Mixed Integer Programming (MIP) model was developed using the LINGO package to find the optimal lane group combinations at an isolated signalized intersection for any given volume using an objective function of minimizing intersection delay. A comparison was conducted between both models by running the models in hypothetical turning movement volumes. It was found that both models are giving exactly the same results.

6.2 Developing a Quick Method to Predict the Optimum Lane Group Combinations

The model was executed, as explained in Figure 3.2, in the afternoon peak hour volumes and then in the evening peak hour volumes since these peak periods have the highest intersection volumes compared to the morning peak period. A third run was executed in a hypothetical peak hour volume, in which the highest observed traffic volume (evening peak period) was assigned to the west and north approaches while the opposing approaches (i.e. east and south) were assigned 30% and 50% of the highest observed volume at these approaches, respectively. This ensures large practical variations in traffic volumes between the opposing approaches with the same number of lanes. For each run, the percentage of turning volumes were systematically changed at a rate of 10% at each approach. The rate of 10% was based on the fact that this increment will result in more than 600,000 cases of turning volume combinations for each trial, which require one month of parallel execution by high performance computers which are using K-20 Graphics Processing Unit (GPU) cluster. Analytical results showed that the changes in the percentages of turning movements at other approaches will not affect the optimum lane group combination (LGC_o) for a specific turning combination at the specific approach under investigation. Hence, a quick method was identified to predict the LGC_o at 3-lane approaches and 4-lane approaches based only on the percentage of turning movements at the targeted approach regardless of the percentages of turning volumes at the other approaches. The results digested in Figure 3-7 and Figure 3-8 are encouraging to look for logical rules to select the optimum lane group on the basis of turning movement, especially for 3-lane approaches. These figures can be used to generate lookup tables, which can be uploaded to the signal controller and then can be used to predict the optimum lane group directly after detecting/predicting the percentages of turning movements. This finding represents a plausible quick method to predict the optimum lane group in the field instantaneously using the percentage of turning movements at the approach without conducting massive calculations.

A neural network model was developed to find the optimum lane group combination for all intersections using the turning movements as input. A sample of 50,000 turning volume combinations was chosen randomly from each peak hour to train and test the ANN model, with a total of 150,000 turning volumes. 75% of turning volumes sample was used for training and the remaining combinations were used for testing. The optimum topology (number of layers, number of neurons per layer and the type of transfer function) was selected by trial and error procedure. The first step was to choose a simple topology with minimum hidden layers and less number of neurons and then increase the number of neurons and number of hidden layers until reaching a point at which the ANN model can predict the optimum lane group combinations with a reasonable accuracy. The optimum topology for the ANN model was found to be 3 hidden layers with 14 neurons in each layer with an accuracy of 92%.

6.3 Assessment of Supportive Techniques in Implementing DLG

Pre-signals and variable message signs were evaluated as supportive techniques which can facilitate the application of DLG at isolated signalized intersections. The idea of the pre-signals is to give priority to a specific movement or mode before reaching the main signal. For the purpose of DLG application, pre-signals can help in reducing the drivers' weaving maneuver by giving the green time for each lane separately so that the driver will be able to choose the appropriate lane without any conflicts from the traffic on the other lanes. A comparison was conducted between the average approach delay for FLG and DLG after introducing the pre-signal. It was observed that for almost all turning movement percentages, the DLG with pre-signal is better than FLG in terms of average approach delay.

Variable Message Signs (VMS) can significantly support the implementation of DLG by providing drivers with real-time information about the existing lane group configuration while approaching signalized intersections. 300 drivers were interviewed to collect disaggregated socio-economic characteristics data about the drivers, such as age, education level, occupation and driving experience and to evaluate the understanding of the regular commuters with VMS messages about DLG. For interview purposes, two videos (each video was developed for different configurations as shown in Figure 5-1 and Figure 5-2), which emulated the traffic movement at one approach, were introduced to the interviewees and then the interviewer asked them six questions about the VMS signs (three questions for each video) to know if the drivers understood the signs or not. The driver who answered the six questions about the signs correctly was considered as a passed driver, otherwise, he was considered as a failed driver. The effect of drivers' characteristics such as age, occupation, driving experience and education level on their response to VMS, was statistically tested at 95% confidence level using contingency analysis. It was concluded that the education level is the most significant variable that affects the driver response to the messages related to dynamic lane grouping, which were displayed on VMS.

6.4 Recommendations

The following recommendations are made for the researchers after taking the observations of this study into account:

- A complementary study should be conducted to cover all types of approaches with any number of lanes including shared lanes.
- It is highly recommended to use a simulator to find the human factors which significantly affect the driver response to DLG.
- It is recommended to apply this procedure under control condition in real life to have a realistic appraisal of this ITS application.
- It is recommended to study the frequency of applying this technique throughout the day from the operation and safety points of view.

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Appendix A: MATLAB Code

```
    % Load the defined volume for each approach
loadLanesVolumData;

% Load the rest defined variables
loadOtherVariablesData();

lanesDelay = {1:4};
allDelay = (1:4);
fourLanesGroup = {laneGroup1, laneGroup2, laneGroup3, laneGroup4, laneGroup5, laneGroup6,
laneGroup7, laneGroup8, laneGroup9, laneGroup10};
threeLanesGroup = {threeLanesGroup1, threeLanesGroup2, threeLanesGroup3, threeLanesGroup4,
threeLanesGroup5, threeLanesGroup6};
minMaxCR = [];
minMaxCR_Print = [];
minMinID_Print = [];
IDFromMinMaxCR = [];
minMinID = [];
CRFromMinMinID = [];
index = 0;
index2 = 0;
zeorsIndex = 0;
cycleLengthDrawData_ID = [];
laneGroupsDrawData_ID = [];
cycleLengthDrawData_CR = [];
laneGroupsDrawData_CR = [];
CPFromMinMinID = [];

        minCapacityRatio = 1000000;
        %minIntersectionDelay = 1000000;
        minCapacityRatioLane = 1;
        minIntersectionDelayLane = 1;
        index = index + 1;
        index2 = index2 + 1;
        %lanesGroupMaxCapacitRation = [];
        lanesGroupMinIntersectionDelay = [];
        lanesGroupCombination1 = {};
        lanesGroupCombination2 = {};
        lanesGroupCombination3 = {};
        lanesGroupCombination4 = {};
        lanesGroupCL = [];
        lanesGroupCR1 = [];
        lanesGroupCR2 = [];
        lanesGroupCR3 = [];
        lanesGroupCR4 = [];
        lanesGroupGREE1 = [];
        lanesGroupGREE2 = [];
        lanesGroupGREE3 = [];
        lanesGroupGREE4 = [];
        compinations = [];
        leftVolume1 = [];
        throughVolume1 = [];
        rightVolume1 = [];
        leftVolume2 = [];
        throughVolume2 = [];
        rightVolume2 = [];
        leftVolume3 = [];
```

```
 throughVolume3 = [];
 rightVolume3 = [];
 leftVolume4 = [];
 throughVolume41 = [];
 rightVolume4 = [];
 finalIndex = 0;
 totalApproach1Volum = 1388;
 totalApproach2Volum = 630;
 totalApproach3Volum = 1412;
 totalApproach4Volum = 611;
 App1LaneGroupNum = [];
 App2LaneGroupNum = [];
 App3LaneGroupNum = [];
 App4LaneGroupNum = [];
 %skipThisLaneGroup = false;

for i1 = 0.1
    leftVolum1= floor(i1 * totalApproach1Volum);
    for j1 = 0.1:0.1:(0.8-i1)
        throughVolum1 = floor(j1 * totalApproach1Volum);
        rightVolum1 = totalApproach1Volum - leftVolum1 - throughVolum1;

        for i2 = 0.1:0.1:0.8
            leftVolum2= floor(i2 * totalApproach2Volum);
            for j2 = 0.1:0.1:(0.8-i2)
                throughVolum2 = floor(j2 * totalApproach2Volum);
                rightVolum2 = totalApproach2Volum - leftVolum2 - throughVolum2;

                for i3 = 0.1:0.1:0.8
                    leftVolum3 = floor(i3 * totalApproach3Volum);
                    for j3 = 0.1:0.1:(0.8-i3)
                        throughVolum3 = floor(j3 * totalApproach3Volum);
                        rightVolum3 = totalApproach3Volum - leftVolum3 - throughVolum3;

                        for i4 = 0.1:0.1:0.8
                            leftVolum4 = floor(i4 * totalApproach4Volum);
                                for j4 = 0.1:0.1:(0.8-i4)
                                    throughVolum4 = floor(j4 * totalApproach4Volum);
                                    rightVolum4 = totalApproach4Volum - leftVolum4 - throughVolum4;

                                    compIndex = 0;

                                    TEMPlanesGroupCR1 = [];
                                    TEMPlanesGroupCR2 = [];
                                    TEMPlanesGroupCR3 = [];
                                    TEMPlanesGroupCR4 = [];
                                    TEMPlanesGroupGREE1 = [];
                                    TEMPlanesGroupGREE2 = [];
                                    TEMPlanesGroupGREE3 = [];
                                    TEMPlanesGroupGREE4 = [];
                                    TEMPcompinations = [];
                                    TEMPlanesGroupCL = [];
                                    TEMPlanesGroupMinIntersectionDelay = [];
                                    TEMPApp1Lanes = [];
                                    TEMPApp2Lanes = [];
                                    TEMPApp3Lanes = [];
```

```
                        TEMPApp4Lanes = [];

                        for app1Lanes = 1:10

                          group1 = fourLanesGroup{app1Lanes};
                          [group1, shared, skip] = sharedLaneFunction(group1, leftVolum1,
throughVolum1, rightVolum1);

                          if shared == false
                            group1 = volumeDistributionFunction( group1, leftVolum1,
throughVolum1, rightVolum1 );
                          end
                          if skip == false
                            for app2Lanes = 1:6
                              group2 = threeLanesGroup{app2Lanes};
                              [group2, shared, skip] = sharedLaneFunction(group2, leftVolum2,
throughVolum2, rightVolum2);

                              if shared == false
                                group2 = volumeDistributionFunction( group2, leftVolum2,
throughVolum2, rightVolum2 );
                              end
                              if skip == false
                                for app3Lanes = 1:10
                                  group3 = fourLanesGroup{app3Lanes};
                                  [group3, shared, skip] = sharedLaneFunction(group3, leftVolum3,
throughVolum3, rightVolum3);

                                  if shared == false
                                    group3 = volumeDistributionFunction( group3, leftVolum3,
throughVolum3, rightVolum3 );
                                  end
                                  if skip == false
                                    for app4Lanes = 1:6
                                      group4 = threeLanesGroup{app4Lanes};
                                      [group4, shared, skip] = sharedLaneFunction(group4,
leftVolum4, throughVolum4, rightVolum4);

                                      if shared == false
                                        group4 = volumeDistributionFunction( group4, leftVolum4,
throughVolum4, rightVolum4 );
                                      end
                                      if skip == false

                                        compIndex = compIndex + 1;

                                        allVolums = {group1, group2, group3, group4};
                                        [calc, CL, CR1, CR2, CR3, CR4, GREE1, GREE2, GREE3,
GREE4] = calculations(allVolums);

                                        tempCapAndDel = calc;
                                        %comText = strcat(num2str(app1Lanes),
num2str(app2Lanes), num2str(app3Lanes), num2str(app4Lanes));
                                        %str = sprintf('%d', comText);
                                        %TEMPcompinations{compIndex} = comText;
                                        TEMPApp1Lanes(compIndex) = app1Lanes;
```

```
                                        TEMPApp2Lanes(compIndex) = app2Lanes;
                                        TEMPApp3Lanes(compIndex) = app3Lanes;
                                        TEMPApp4Lanes(compIndex) = app4Lanes;

                                        TEMPlanesGroupMaxCapacitRation(compIndex) =
tempCapAndDel(1);
                                        TEMPlanesGroupMinIntersectionDelay(compIndex) =
tempCapAndDel(2);
                                        TEMPlanesGroupCL(compIndex) = CL;

                                        TEMPlanesGroupCR1(compIndex) = CR1;
                                        TEMPlanesGroupCR2(compIndex) = CR2;
                                        TEMPlanesGroupCR3(compIndex) = CR3;
                                        TEMPlanesGroupCR4(compIndex) = CR4;

                                        TEMPlanesGroupGREE1(compIndex) = GREE1;
                                        TEMPlanesGroupGREE2(compIndex) = GREE2;
                                        TEMPlanesGroupGREE3(compIndex) = GREE3;
                                        TEMPlanesGroupGREE4(compIndex) = GREE4;
                                      end
                                    end
                                  end
                                end
                              end
                            end
                          end
                        end

                        finalIndex = finalIndex + 1;
                        [miIDValue,minMinID_Index] = min(TEMPlanesGroupMinIntersectionDelay);
                        lanesGroupMinIntersectionDelay(finalIndex) = miIDValue;

                        %lanesGroupMaxCapacitRation(finalIndex) =
TEMPlanesGroupMaxCapacitRation(minMinID_Index);

                        %compinations{finalIndex} = TEMPcompinations{minMinID_Index};

                        lanesGroupCL(finalIndex) = TEMPlanesGroupCL(minMinID_Index);

                        lanesGroupCR1(finalIndex) = TEMPlanesGroupCR1(minMinID_Index);
                        lanesGroupCR2(finalIndex) = TEMPlanesGroupCR2(minMinID_Index);
                        lanesGroupCR3(finalIndex) = TEMPlanesGroupCR3(minMinID_Index);
                        lanesGroupCR4(finalIndex) = TEMPlanesGroupCR4(minMinID_Index);

                        lanesGroupGREE1(finalIndex) = TEMPlanesGroupGREE1(minMinID_Index);
                        lanesGroupGREE2(finalIndex) = TEMPlanesGroupGREE2(minMinID_Index);
                        lanesGroupGREE3(finalIndex) = TEMPlanesGroupGREE3(minMinID_Index);
                        lanesGroupGREE4(finalIndex) = TEMPlanesGroupGREE4(minMinID_Index);

                        leftVolume1(finalIndex) = leftVolum1;
                        leftVolume2(finalIndex) = leftVolum2;
                        leftVolume3(finalIndex) = leftVolum3;
                        leftVolume4(finalIndex) = leftVolum4;

                        throughVolume1(finalIndex) = throughVolum1;
                        throughVolume2(finalIndex) = throughVolum2;
```

```
                            throughVolume3(finalIndex) = throughVolum3;
                            throughVolume4(finalIndex) = throughVolum4;

                            rightVolume1(finalIndex) = rightVolum1;
                            rightVolume2(finalIndex) = rightVolum2;
                            rightVolume3(finalIndex) = rightVolum3;
                            rightVolume4(finalIndex) = rightVolum4;

                            App1LaneGroupNum(finalIndex) = TEMPApp1Lanes(minMinID_Index);
                            App2LaneGroupNum(finalIndex) = TEMPApp2Lanes(minMinID_Index);
                            App3LaneGroupNum(finalIndex) = TEMPApp3Lanes(minMinID_Index);
                            App4LaneGroupNum(finalIndex) = TEMPApp4Lanes(minMinID_Index);
                        end
                    end
                end
            end
        end
    end
  end
end


unction [ calc, CL, CR1, CR2, CR3, CR4, GR1, GR2, GR3, GR4 ] = calculations( allVolums)

  global turningRadius;
  global lostTime;
  sumationOfLaneVloumes = {1:4}; % this used in flow factor calculation
  allFlowFactors = {1:4};
  allSaturations = {1:4};
  allFlowRatio = {1:4};
  maxFlowRatioSum = 0;
  allGreenTime = (1:4);
  allCapacityRatio = {1:4};
  CL = 0;
  GREE = 0;

  % Clculate volume sumation for each lane
  for i = 1:4
    volum = allVolums{i};
    for k = 1:length(volum(:,:))
      sum = 0;
      for m = 1:3
        sum = sum + volum(m,k);
      end
      summation(k) = sum;
    end
    sumationOfLaneVloumes{i} = summation;
    clearvars summation;
  end

  for i = 1:4
    allFlowFactors{i} = flowFactorFunction(allVolums{i}, sumationOfLaneVloumes{i});
    allSaturations{i} = saturationFlowRate(allFlowFactors{i}, turningRadius);
    allFlowRatio{i} = flowRationFunction(sumationOfLaneVloumes{i}, allSaturations{i});
    maxFlowRatioSum = maxFlowRatioSum + max(allFlowRatio{i});
  end
```

```
    %%
    % Print Saturation and Flowfactor
    %disp(allSaturations{1});
    %disp(allSaturations{2});
    %disp(allSaturations{3});
    %disp(allSaturations{4});

    %disp(allFlowFactors{1});
    %disp(allFlowFactors{2});
    %disp(allFlowFactors{3});
    %disp(allFlowFactors{4});


    %cycleLength = 1.5 * lostTime * exp(1.8 * maxFlowRatioSum);
    %app1Saturation = allSaturations{1};

    %if cycleLength > 250
      %cycleLength = 250;
    %end

    tempLoopIndex = 0;
    tempcycleLengthArray = [];
    tempApproachDelayArray = [];
    tempIntersectionDelayArray = [];
    tempAllCapacityRatio = {};
    tempApp1CR = {};
    tempApp2CR = {};
    tempApp3CR = {};
    tempApp4CR = {};
    TEMPGREEN1 = [];
    TEMPGREEN2 = [];
    TEMPGREEN3 = [];
    TEMPGREEN4 = [];

    for cycleLength = 60:5:250
      tempLoopIndex = tempLoopIndex + 1;
      tempcycleLengthArray(tempLoopIndex) = cycleLength;

      effectiveGreenTime = cycleLength - lostTime;

      for i = 1:4
        allGreenTime(i) = (max(allFlowRatio{i}) / maxFlowRatioSum) * effectiveGreenTime;
        allCapacityRatio{i} = capacityRatioFunction(sumationOfLaneVloumes{i},
allGreenTime(i),cycleLength, allSaturations{i});
        lanesDelay{i} = delayFunction(sumationOfLaneVloumes{i}, allCapacityRatio{i}, allGreenTime(i),
cycleLength, allSaturations{i}, i );
      end

      TEMPGREEN1(tempLoopIndex) = allGreenTime(1);
      TEMPGREEN2(tempLoopIndex) = allGreenTime(2);
      TEMPGREEN3(tempLoopIndex) = allGreenTime(3);
      TEMPGREEN4(tempLoopIndex) = allGreenTime(4);

      approachsDalay = 0;
      intersectionVolum = 0;
```

```
        for i = 1:4
            lDelay = lanesDelay{i};
            volum = sumationOfLaneVloumes{i};
            volumSum = 0;
            delaySum = 0;

            for k = 1:length(volum(:,:))
                delaySum = delaySum + lDelay(k);
                volumSum = volumSum + volum(k);
            end
            allDelay (i) = delaySum / volumSum; % Approach delay
            intersectionVolum = intersectionVolum + volumSum;
            approachsDalay = approachsDalay + delaySum;
        end
        tempIntersectionDelayArray(tempLoopIndex) = approachsDalay / intersectionVolum; % Intersection
Delay
        tempApproachDelayArray(tempLoopIndex) = allDelay(1);
        tempAllCapacityRatio{tempLoopIndex} = allCapacityRatio{1};
        tempApp1CR{tempLoopIndex} = allCapacityRatio{1};
        tempApp2CR{tempLoopIndex} = allCapacityRatio{2};
        tempApp3CR{tempLoopIndex} = allCapacityRatio{3};
        tempApp4CR{tempLoopIndex} = allCapacityRatio{4};
    end

    [minIntersectionDelayValue,minIntersectionDelayIndex] = min(tempIntersectionDelayArray);
    %tempApproachDelayArray(minIntersectionDelayIndex);
    tempcycleLengthArray(minIntersectionDelayIndex);


    CR1 = max(tempApp1CR{minIntersectionDelayIndex});
    CR2 = max(tempApp2CR{minIntersectionDelayIndex});
    CR3 = max(tempApp3CR{minIntersectionDelayIndex});
    CR4 = max(tempApp4CR{minIntersectionDelayIndex});

    GR1 = TEMPGREEN1(minIntersectionDelayIndex);
    GR2 = TEMPGREEN2(minIntersectionDelayIndex);
    GR3 = TEMPGREEN3(minIntersectionDelayIndex);
    GR4 = TEMPGREEN4(minIntersectionDelayIndex);


    %calc(1) = max(allCapacityRatio{1});
    calc(1) = max(tempAllCapacityRatio{minIntersectionDelayIndex});
    calc(2) = minIntersectionDelayValue;
    CL =  tempcycleLengthArray(minIntersectionDelayIndex);
    %GREE = TEMPGREEN(minIntersectionDelayIndex);
end
```

Appendix B: Lingo script for the developed MIP model

```
Model:
Title: ;
SETS:
   Approach /1..4/;
   CONFIG/1..5/;
   LANE/1..4/;
   CONF_1 /1..5/: MAXAM_1;
   CONF_2 /1..3/: MAXAM_2;
   CONF_3 /1..5/: MAXAM_3;
   CONF_4 /1..3/: MAXAM_4;
   LANE_1/1..4/;
   LANE_2/1..3/;
   LANE_3/1..4/;
   LANE_4/1..3/;



   MOVEMENT/1,2,3/;
   LINKS1(Approach, MOVEMENT): V;
   LINKS11(Approach): VT;
   LINKS2(APPROACH,MOVEMENT, CONFIG):  X;
   LINKS6(Approach, CONF_1, CONF_2, CONF_3, CONF_4): RATIO,AD;
   LINKS66(CONF_1, CONF_2, CONF_3, CONF_4) :B;
   LINKS7(Approach, CONF_1, CONF_2, CONF_3, CONF_4, LANE_1 ): D_1;
   LINKS8(Approach, CONF_1, CONF_2, CONF_3, CONF_4, LANE_2 ): D_2;
   LINKS9(Approach, CONF_1, CONF_2, CONF_3, CONF_4, LANE_3 ): D_3;
   LINKS10(Approach,CONF_1, CONF_2, CONF_3, CONF_4, LANE_4 ): D_4;

ENDSETS



 min =Y;
[DELAY]Y=@SUM(CONF_1(I):@SUM(CONF_2(J):@SUM(CONF_3(K):@SUM(CONF_4(Z
):
B(I,J,K,Z)*@SUM(Approach(A):VT(A)*AD(A,I,J,K,Z))))))/(VT(1)+VT(2)+VT(3)+VT(4));

@sum(conf_1(I):
@sum(conf_2(J):
@sum(conf_3(K):
@sum(conf_4(Z):
B(I,J,K,Z))))) = 1;

@FOR(CONF_1(I):
@FOR(CONF_2(J):
```

```
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
@BIN(B(I,J,K,Z))))));


@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
RATIO(1,I,J,K,Z)=
MAXAM_1(I)/(MAXAM_1(I)+MAXAM_2(J)+MAXAM_3(K)+MAXAM_4(Z))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
RATIO(2,I,J,K,Z)=
MAXAM_2(J)/(MAXAM_1(I)+MAXAM_2(J)+MAXAM_3(K)+MAXAM_4(Z))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
RATIO(3,I,J,K,Z)=
MAXAM_3(K)/(MAXAM_1(I)+MAXAM_2(J)+MAXAM_3(K)+MAXAM_4(Z))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
RATIO(4,I,J,K,Z)=
MAXAM_4(Z)/(MAXAM_1(I)+MAXAM_2(J)+MAXAM_3(K)+MAXAM_4(Z))))));


MAXAM_1(1)=@SMAX((9*V(1,1)+8*X(1,1,1))/15200,(V(1,2)-X(1,1,1)-
X(1,3,1))/3800,(23*V(1,3)+20*X(1,3,1))/38000);
MAXAM_1(2)=@SMAX((9*V(1,1)+8*V(1,2))/15200,V(1,3)/4956.51);
MAXAM_1(3)=@SMAX(V(1,1)/5066.67,(23*V(1,3)+20*V(1,2))/38000);
MAXAM_1(4)=@SMAX((9*V(1,1)+8*X(1,1,4))/15200,(V(1,2)-X(1,1,4))/1900,V(1,3)/3304.34);
MAXAM_1(5)=@SMAX(V(1,1)/3377.78,(V(1,2)-X(1,3,5))/1900,(23*V(1,3)+20*X(1,3,5))/38000);

MAXAM_2(1)=@SMAX((9*V(2,1)+8*X(2,1,1))/15200,(V(2,2)-X(2,1,1)-
X(2,3,1))/1900,(23*V(2,3)+20*X(2,3,1))/38000);
MAXAM_2(2)=@SMAX((9*V(2,1)+8*V(2,2))/15200,V(2,3)/3304.34);
MAXAM_2(3)=@SMAX(V(2,1)/5066.67,(23*V(2,3)+20*V(2,2))/38000);

MAXAM_3(1)=@SMAX((9*V(3,1)+8*X(3,1,1))/15200,(V(3,2)-X(3,1,1)-
X(3,3,1))/3800,(23*V(3,3)+20*X(3,3,1))/38000);
MAXAM_3(2)=@SMAX((9*V(3,1)+8*V(3,2))/15200,V(3,3)/4956.51);
MAXAM_3(3)=@SMAX(V(3,1)/5066.67,(23*V(3,3)+20*V(3,2))/38000);
```

```
MAXAM_3(4)=@SMAX((9*V(3,1)+8*X(3,1,4))/15200,(V(3,2)-X(3,1,4))/1900,V(3,3)/3304.34);
MAXAM_3(5)=@SMAX(V(3,1)/3377.78,(V(3,2)-X(3,3,5))/1900,(23*V(3,3)+20*X(3,3,5))/38000);

MAXAM_4(1)=@SMAX((9*V(4,1)+8*X(4,1,1))/15200,(V(4,2)-X(4,1,1)-
X(4,3,1))/1900,(23*V(4,3)+20*X(4,3,1))/38000);
MAXAM_4(2)=@SMAX((9*V(4,1)+8*V(4,2))/15200,V(4,3)/3304.34);
MAXAM_4(3)=@SMAX(V(4,1)/5066.67,(23*V(4,3)+20*V(4,2))/38000);


SL=1688.89;
ST=1900;
SR=1652.17;
VT(1)= V(1,1)+V(1,2)+V(1,3);
VT(2)= V(2,1)+V(2,2)+V(2,3);
VT(3)= V(3,1)+V(3,2)+V(3,3);
VT(4)= V(4,1)+V(4,2)+V(4,3);


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
AD(1,1,J,K,Z)= ((V(1,1)+X(1,1,1))*D_1(1,1,J,K,Z,1)+ (V(1,2)-X(1,1,1)-X(1,3,1))*
D_1(1,1,J,K,Z,2)+ (V(1,3)+X(1,3,1))*D_1(1,1,J,K,Z,4))/VT(1))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
AD(1,2,J,K,Z)=((V(1,1)+V(1,2))* D_1(1,2,J,K,Z,1)+ V(1,3)* D_1(1,2,J,K,Z,2))/VT(1))));

@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
AD(1,3,J,K,Z)=(V(1,1)* D_1(1,3,J,K,Z,1)+(V(1,3)+V(1,2))* D_1(1,3,J,K,Z,4))/VT(1))));

@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
AD(1,4,J,K,Z)=((V(1,1)+X(1,1,4))* D_1(1,4,J,K,Z,1)+ (V(1,2)-X(1,1,4))*D_1(1,4,J,K,Z,2)+
V(1,3) * D_1(1,4,J,K,Z,3))/VT(1))));

@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
AD(1,5,J,K,Z)=(V(1,1)* D_1(1,5,J,K,Z,1) + (V(1,2)-X(1,3,5))* D_1(1,5,J,K,Z,3)+
(V(1,3)+X(1,3,5))*D_1(1,5,J,K,Z,4))/VT(1))));

@FOR(CONF_2(J):
@FOR(CONF_3(K):
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@FOR(CONF_4(Z):
D_1(1,1,J,K,Z,1)= (0.5*C*(1-RATIO(1,1,J,K,Z)*(C-18)/C)^2)/(1-
(@smin(1,(((9*V(1,1)+8*X(1,1,1))*C)  /(15200*RATIO(1,1,J,K,Z)*(C-18))))*(RATIO(1,1,J,K,Z)*(C-
18)/C)))+ 900*((((9*V(1,1)+8*X(1,1,1))*C)  /(15200*RATIO(1,1,J,K,Z)*(C-18)))-
1)+900*@SQRT((((((9*V(1,1)+8*X(1,1,1))*C)  /(15200*RATIO(1,1,J,K,Z)*(C-18)))-
1)^2)+(4*((((9*V(1,1)+8*X(1,1,1))*C)/(15200*RATIO(1,1,J,K,Z)*(C-18)))^2/(V(1,1)+X(1,1,1))))))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_1(1,1,J,K,Z,2)= 0.5*C*(1-RATIO(1,1,J,K,Z)*(C-18)/C)^2/(1-@smin(1,((V(1,2)-X(1,1,1)-
X(1,3,1))/(3800*RATIO(1,1,J,K,Z)-(68400*RATIO(1,1,J,K,Z)/C))))*RATIO(1,1,J,K,Z)*(c-18)/C)+
900*(((V(1,2)-X(1,1,1)-X(1,3,1))/(3800*RATIO(1,1,J,K,Z)-(68400*RATIO(1,1,J,K,Z)/C))-
1)+@sqrt((((V(1,2)-X(1,1,1)-X(1,3,1))/(3800*RATIO(1,1,J,K,Z)-(68400*RATIO(1,1,J,K,Z)/C))-
1)^2)+2*(V(1,2)-X(1,1,1)-X(1,3,1))/(1900*RATIO(1,1,J,K,Z)-(34200*RATIO(1,1,J,K,Z))/C)^2)))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_1(1,1,J,K,Z,3)= 0.5*C*(1-RATIO(1,1,J,K,Z)*(C-18)/C)^2/(1-@smin(1,((V(1,2)-X(1,1,1)-
X(1,3,1))/(3800*RATIO(1,1,J,K,Z)-(68400*RATIO(1,1,J,K,Z)/C))))*RATIO(1,1,J,K,Z)*(c-18)/C)+
900*(((V(1,2)-X(1,1,1)-X(1,3,1))/(3800*RATIO(1,1,J,K,Z)-(68400*RATIO(1,1,J,K,Z)/C))-
1)+@sqrt((((V(1,2)-X(1,1,1)-X(1,3,1))/(3800*RATIO(1,1,J,K,Z)-(68400*RATIO(1,1,J,K,Z)/C))-
1)^2)+2*(V(1,2)-X(1,1,1)-X(1,3,1))/(1900*RATIO(1,1,J,K,Z)-(34200*RATIO(1,1,J,K,Z))/C)^2)))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_1(1,1,J,K,Z,4)= (0.5*C*(1-RATIO(1,1,J,K,Z)*(C-18)/C)^2)/(1-
(@sMin(1,(((23*V(1,3)+20*X(1,3,1))*C)/(38000*RATIO(1,1,J,K,Z)*(C-18))))*(RATIO(1,1,J,K,Z)*(C-
18)/C)))+ 900*((((23*V(1,3)+20*X(1,3,1))*C)/(38000*RATIO(1,1,J,K,Z)*(C-18)))-
1)+900*@sqrt((((((23*V(1,3)+20*X(1,3,1))*C)/(38000*RATIO(1,1,J,K,Z)*(C-18)))-
1)^2)+(4*((((23*V(1,3)+20*X(1,3,1))*C)/(38000*RATIO(1,1,J,K,Z)*(C-18)))^2/(V(1,3)+X(1,3,1))))))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_1(1,2,J,K,Z,1)= (0.5*C*(1-RATIO(1,2,J,K,Z)*(C-18)/C)^2)/(1-
(@smin(1,(((9*V(1,1)+8*V(1,2))*C) /(15200*RATIO(1,2,J,K,Z)*(C-18))))*(RATIO(1,2,J,K,Z)*(C-
18)/C)))+ 900*((((9*V(1,1)+8*V(1,2))*C) /(15200*RATIO(1,2,J,K,Z)*(C-18)))-
1)+900*@sqrt((((((9*V(1,1)+8*V(1,2))*C)   /(15200*RATIO(1,2,J,K,Z)*(C-18)))-
1)^2)+(4*((((9*V(1,1)+8*V(1,2))*C)/(15200*RATIO(1,2,J,K,Z)*(C-18)))^2/(V(1,1)+V(1,2))))))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
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D_1(1,2,J,K,Z,2)= 0.5*C*(1-RATIO(1,2,J,K,Z)*(C-18)/C)^2/(1-
@smin(1,(V(1,3)/(4956.51*RATIO(1,2,J,K,Z)-(89217.18*RATIO(1,2,J,K,Z)/C))))*RATIO(1,2,J,K,Z)*(c-
18)/C)+900*((V(1,3)/(4956.51*RATIO(1,2,J,K,Z)-(89217.18*RATIO(1,2,J,K,Z)/C))-
1)+@sqrt(((V(1,3)/(4956.51*RATIO(1,2,J,K,Z)-(89217.18*RATIO(1,2,J,K,Z)/C))-
1)^2)+4*V(1,3)/(3*(1652.17*RATIO(1,2,J,K,Z)-(29739.06*RATIO(1,2,J,K,Z))/C)^2))))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_1(1,2,J,K,Z,3)= 0.5*C*(1-RATIO(1,2,J,K,Z)*(C-18)/C)^2/(1-
@smin(1,(V(1,3)/(4956.51*RATIO(1,2,J,K,Z)-(89217.18*RATIO(1,2,J,K,Z)/C))))*RATIO(1,2,J,K,Z)*(c-
18)/C)+900*((V(1,3)/(4956.51*RATIO(1,2,J,K,Z)-(89217.18*RATIO(1,2,J,K,Z)/C))-
1)+@sqrt(((V(1,3)/(4956.51*RATIO(1,2,J,K,Z)-(89217.18*RATIO(1,2,J,K,Z)/C))-
1)^2)+4*V(1,3)/(3*(1652.17*RATIO(1,2,J,K,Z)-(29739.06*RATIO(1,2,J,K,Z))/C)^2))))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_1(1,2,J,K,Z,4)= 0.5*C*(1-RATIO(1,2,J,K,Z)*(C-18)/C)^2/(1-
@smin(1,(V(1,3)/(4956.51*RATIO(1,2,J,K,Z)-(89217.18*RATIO(1,2,J,K,Z)/C))))*RATIO(1,2,J,K,Z)*(c-
18)/C)+900*((V(1,3)/(4956.51*RATIO(1,2,J,K,Z)-(89217.18*RATIO(1,2,J,K,Z)/C))-
1)+@sqrt(((V(1,3)/(4956.51*RATIO(1,2,J,K,Z)-(89217.18*RATIO(1,2,J,K,Z)/C))-
1)^2)+4*V(1,3)/(3*(1652.17*RATIO(1,2,J,K,Z)-(29739.06*RATIO(1,2,J,K,Z))/C)^2))))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_1(1,3,J,K,Z,1)= 0.5*C*(1-RATIO(1,3,J,K,Z)*(C-18)/C)^2/(1-
@smin(1,(V(1,1)/(5066.67*RATIO(1,3,J,K,Z)-(91200.06*RATIO(1,3,J,K,Z)/C))))*RATIO(1,3,J,K,Z)*(c-
18)/C)+900*((V(1,1)/(5066.67*RATIO(1,3,J,K,Z)-(91200.06*RATIO(1,3,J,K,Z)/C))-
1)+@sqrt(((V(1,1)/(5066.67*RATIO(1,3,J,K,Z)-(91200.06*RATIO(1,3,J,K,Z)/C))-
1)^2)+4*V(1,1)/(3*(1688.89*RATIO(1,3,J,K,Z)-(30400.02*RATIO(1,3,J,K,Z))/C)^2))))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_1(1,3,J,K,Z,2)= 0.5*C*(1-RATIO(1,3,J,K,Z)*(C-18)/C)^2/(1-
@smin(1,(V(1,1)/(5066.67*RATIO(1,3,J,K,Z)-(91200.06*RATIO(1,3,J,K,Z)/C))))*RATIO(1,3,J,K,Z)*(c-
18)/C)+900*((V(1,1)/(5066.67*RATIO(1,3,J,K,Z)-(91200.06*RATIO(1,3,J,K,Z)/C))-
1)+@sqrt(((V(1,1)/(5066.67*RATIO(1,3,J,K,Z)-(91200.06*RATIO(1,3,J,K,Z)/C))-
1)^2)+4*V(1,1)/(3*(1688.89*RATIO(1,3,J,K,Z)-(30400.02*RATIO(1,3,J,K,Z))/C)^2))))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
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```
D_1(1,3,J,K,Z,3)= 0.5*C*(1-RATIO(1,3,J,K,Z)*(C-18)/C)^2/(1-
@smin(1,(V(1,1)/(5066.67*RATIO(1,3,J,K,Z)-(91200.06*RATIO(1,3,J,K,Z)/C))))*RATIO(1,3,J,K,Z)*(c-
18)/C)+900*((V(1,1)/(5066.67*RATIO(1,3,J,K,Z)-(91200.06*RATIO(1,3,J,K,Z)/C))-
1)+@sqrt(((V(1,1)/(5066.67*RATIO(1,3,J,K,Z)-(91200.06*RATIO(1,3,J,K,Z)/C))-
1)^2)+4*V(1,1)/(3*(1688.89*RATIO(1,3,J,K,Z)-(30400.02*RATIO(1,3,J,K,Z))/C)^2))))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_1(1,3,J,K,Z,4)= (0.5*C*(1-RATIO(1,3,J,K,Z)*(C-18)/C)^2)/(1-
(@sMin(1,(((23*V(1,3)+20*V(1,2))*C)/(38000*RATIO(1,3,J,K,Z)*(C-18))))*(RATIO(1,3,J,K,Z)*(C-
18)/C)))+ 900*((((23*V(1,3)+20*V(1,2))*C)/(38000*RATIO(1,3,J,K,Z)*(C-18)))-
1)+900*@sqrt((((((23*V(1,3)+20*V(1,2))*C/(38000*RATIO(1,3,J,K,Z)*(C-18)))-1)^2)+
(4*((((23*V(1,3)+20*V(1,2))*C)/(38000*RATIO(1,3,J,K,Z)*(C-18)))^2/(V(1,3)+V(1,2)))))))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_1(1,4,J,K,Z,1)= (0.5*C*(1-RATIO(1,4,J,K,Z)*(C-18)/C)^2)/(1-
(@smin(1,(((9*V(1,1)+8*X(1,1,4))*C)  /(15200*RATIO(1,4,J,K,Z)*(C-18))))*(RATIO(1,4,J,K,Z)*(C-
18)/C)))+ 900*((((9*V(1,1)+8*X(1,1,4))*C)  /(15200*RATIO(1,4,J,K,Z)*(C-18)))-
1)+900*@SQRT((((((9*V(1,1)+8*X(1,1,4))*C)  /(15200*RATIO(1,4,J,K,Z)*(C-18)))-
1)^2)+(4*((((9*V(1,1)+8*X(1,1,4))*C)/(15200*RATIO(1,4,J,K,Z)*(C-18)))^2/(V(1,1)+X(1,1,4))))))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_1(1,4,J,K,Z,2)= 0.5*C*(1-RATIO(1,4,J,K,Z)*(C-18)/C)^2/(1-@smin(1,((V(1,2)-
X(1,1,4))/(1900*RATIO(1,4,J,K,Z)-(34200*RATIO(1,4,J,K,Z)/C))))*RATIO(1,4,J,K,Z)*(c-18)/C)+
900*(((V(1,2)-X(1,1,4))/(1900*RATIO(1,4,J,K,Z)-(34200*RATIO(1,4,J,K,Z)/C))-1)+@sqrt((((V(1,2)-
X(1,1,4))/(1900*RATIO(1,4,J,K,Z)-(34200*RATIO(1,4,J,K,Z)/C))-1)^2)+4*(V(1,2)-
X(1,1,4))/(1900*RATIO(1,4,J,K,Z)-(34200*RATIO(1,4,J,K,Z))/C)^2)))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_1(1,4,J,K,Z,3)= 0.5*C*(1-RATIO(1,4,J,K,Z)*(C-18)/C)^2/(1-
@smin(1,(V(1,3)/(3304.34*RATIO(1,4,J,K,Z)-(59478.12*RATIO(1,4,J,K,Z)/C))))*RATIO(1,4,J,K,Z)*(c-
18)/C)+900*((V(1,3)/(3304.34*RATIO(1,4,J,K,Z)-(59478.12*RATIO(1,4,J,K,Z)/C))-
1)+@sqrt(((V(1,3)/(3304.34*RATIO(1,4,J,K,Z)-(59478.12*RATIO(1,4,J,K,Z)/C))-
1)^2)+2*V(1,3)/(1652.17*RATIO(1,4,J,K,Z)-(29739.06*RATIO(1,4,J,K,Z))/C)^2)))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_1(1,4,J,K,Z,4)= 0.5*C*(1-RATIO(1,4,J,K,Z)*(C-18)/C)^2/(1-
@smin(1,(V(1,3)/(3304.34*RATIO(1,4,J,K,Z)-(59478.12*RATIO(1,4,J,K,Z)/C))))*RATIO(1,4,J,K,Z)*(c-
```

```
18)/C)+900*((V(1,3)/(3304.34*RATIO(1,4,J,K,Z)-(59478.12*RATIO(1,4,J,K,Z)/C))-
1)+@sqrt(((V(1,3)/(3304.34*RATIO(1,4,J,K,Z)-(59478.12*RATIO(1,4,J,K,Z)/C))-
1)^2)+2*V(1,3)/(1652.17*RATIO(1,4,J,K,Z)-(29739.06*RATIO(1,4,J,K,Z))/C)^2)))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_1(1,5,J,K,Z,1)= 0.5*C*(1-RATIO(1,5,J,K,Z)*(C-18)/C)^2/(1-
@smin(1,(V(1,1)/(3377.78*RATIO(1,5,J,K,Z)-(60800.04*RATIO(1,5,J,K,Z)/C))))*RATIO(1,5,J,K,Z)*(c-
18)/C)+900*((V(1,1)/(3377.78*RATIO(1,5,J,K,Z)-(60800.04*RATIO(1,5,J,K,Z)/C))-
1)+@sqrt(((V(1,1)/(3377.78*RATIO(1,5,J,K,Z)-(60800.04*RATIO(1,5,J,K,Z)/C))-
1)^2)+2*V(1,1)/(1688.89*RATIO(1,5,J,K,Z)-(30400.02*RATIO(1,5,J,K,Z))/C)^2)))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_1(1,5,J,K,Z,2)= 0.5*C*(1-RATIO(1,5,J,K,Z)*(C-18)/C)^2/(1-
@smin(1,(V(1,1)/(3377.78*RATIO(1,5,J,K,Z)-(60800.04*RATIO(1,5,J,K,Z)/C))))*RATIO(1,5,J,K,Z)*(c-
18)/C)+900*((V(1,1)/(3377.78*RATIO(1,5,J,K,Z)-(60800.04*RATIO(1,5,J,K,Z)/C))-
1)+@sqrt(((V(1,1)/(3377.78*RATIO(1,5,J,K,Z)-(60800.04*RATIO(1,5,J,K,Z)/C))-
1)^2)+2*V(1,1)/(1688.89*RATIO(1,5,J,K,Z)-(30400.02*RATIO(1,5,J,K,Z))/C)^2)))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_1(1,5,J,K,Z,3)= 0.5*C*(1-RATIO(1,5,J,K,Z)*(C-18)/C)^2/(1-@smin(1,((V(1,2)-
X(1,3,5))/(1900*RATIO(1,5,J,K,Z)-(34200*RATIO(1,5,J,K,Z)/C))))*RATIO(1,5,J,K,Z)*(c-18)/C)+
900*(((V(1,2)-X(1,3,5))/(1900*RATIO(1,5,J,K,Z)-(34200*RATIO(1,5,J,K,Z)/C))-1)+@sqrt((((V(1,2)-
X(1,3,5))/(1900*RATIO(1,5,J,K,Z)-(34200*RATIO(1,5,J,K,Z)/C))-1)^2)+4*(V(1,2)-
X(1,3,5))/(1900*RATIO(1,5,J,K,Z)-(34200*RATIO(1,5,J,K,Z))/C)^2)))));


@FOR(CONF_2(J):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_1(1,5,J,K,Z,4)= (0.5*C*(1-RATIO(1,5,J,K,Z)*(C-18)/C)^2)/(1-
(@sMin(1,(((23*V(1,3)+20*X(1,3,5))*C)/(38000*RATIO(1,5,J,K,Z)*(C-18))))*(RATIO(1,5,J,K,Z)*(C-
18)/C)))+ 900*((((23*V(1,3)+20*X(1,3,5))*C)/(38000*RATIO(1,5,J,K,Z)*(C-18)))-
1)+900*@sqrt((((((23*V(1,3)+20*X(1,3,5))*C)/(38000*RATIO(1,5,J,K,Z)*(C-18)))-
1)^2)+(4*((((23*V(1,3)+20*X(1,3,5))*C)/(38000*RATIO(1,5,J,K,Z)*(C-18)))^2/(V(1,3)+X(1,3,5))))))));


@FOR(CONF_1(I):
@FOR(CONF_3(K):
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@FOR(CONF_4(Z):
AD(2,I,1,K,Z)= ((V(2,1)+X(2,1,1))*D_2(2,I,1,K,Z,1)+ (V(2,2)-X(2,1,1)-
X(2,3,1))*D_2(2,I,1,K,Z,2)+ (V(2,3)+X(2,3,1))* D_2(2,I,1,K,Z,3))/VT(2))));

@FOR(CONF_1(I):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
AD(2,I,2,K,Z)= ((V(2,1)+V(2,2))* D_2(2,I,2,K,Z,1)+ V(2,3)* D_2(2,I,2,K,Z,2))/VT(2))));

@FOR(CONF_1(I):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
AD(2,I,3,K,Z)= (V(2,1)* D_2(2,I,3,K,Z,1)+(V(2,3)+V(2,2))*D_2(2,I,3,K,Z,3))/VT(2))));


@FOR(CONF_1(I):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_2(2,I,1,K,Z,1)= (0.5*C*(1-RATIO(2,I,1,K,Z)*(C-18)/C)^2)/(1-
(@smin(1,(((9*V(2,1)+8*X(2,1,1))*C)  /(15200*RATIO(2,I,1,K,Z)*(C-18))))*(RATIO(2,I,1,K,Z)*(C-
18)/C)))+ 900*((((9*V(2,1)+8*X(2,1,1))*C)  /(15200*RATIO(2,I,1,K,Z)*(C-18)))-
1)+900*@SQRT((((((9*V(2,1)+8*X(2,1,1))*C)  /(15200*RATIO(2,I,1,K,Z)*(C-18)))-
1)^2)+(4*((((9*V(2,1)+8*X(2,1,1))*C)/(15200*RATIO(2,I,1,K,Z)*(C-18)))^2/(V(2,1)+X(2,1,1))))))));


@FOR(CONF_1(I):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_2(2,I,1,K,Z,2)= 0.5*C*(1-RATIO(2,I,1,K,Z)*(C-18)/C)^2/(1-@smin(1,((V(2,2)-X(2,1,1)-
X(2,3,1))/(1900*RATIO(2,I,1,K,Z)-(34200*RATIO(2,I,1,K,Z)/C))))*RATIO(2,I,1,K,Z)*(c-18)/C)+
900*(((V(2,2)-X(2,1,1)-X(2,3,1))/(1900*RATIO(2,I,1,K,Z)-(34200*RATIO(2,I,1,K,Z)/C))-
1)+@sqrt((((V(2,2)-X(2,1,1)-X(2,3,1))/(1900*RATIO(2,I,1,K,Z)-(34200*RATIO(2,I,1,K,Z)/C))-
1)^2)+4*(V(2,2)-X(2,1,1)-X(2,3,1))/(1900*RATIO(2,I,1,K,Z)-(34200*RATIO(2,I,1,K,Z))/C)^2)))));


@FOR(CONF_1(I):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_2(2,I,1,K,Z,3)= (0.5*C*(1-RATIO(2,I,1,K,Z)*(C-18)/C)^2)/(1-
(@sMin(1,(((23*V(2,3)+20*X(2,3,1))*C)/(38000*RATIO(2,I,1,K,Z)*(C-18))))*(RATIO(2,I,1,K,Z)*(C-
18)/C)))+ 900*((((23*V(2,3)+20*X(2,3,1))*C)/(38000*RATIO(2,I,1,K,Z)*(C-18)))-
1)+900*@sqrt((((((23*V(2,3)+20*X(2,3,1))*C)/(38000*RATIO(2,I,1,K,Z)*(C-18)))-
1)^2)+(4*((((23*V(2,3)+20*X(2,3,1))*C)/(38000*RATIO(2,I,1,K,Z)*(C-18)))^2/(V(2,3)+X(2,3,1))))))));

@FOR(CONF_1(I):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_2(2,I,2,K,Z,1)= (0.5*C*(1-RATIO(2,I,2,K,Z)*(C-18)/C)^2)/(1-(@smin(1,(((9*V(2,1)+8*V(2,2))*C)
/(15200*RATIO(2,I,2,K,Z)*(C-18))))*(RATIO(2,I,2,K,Z)*(C-18)/C)))+ 900*((((9*V(2,1)+8*V(2,2))*C)
/(15200*RATIO(2,I,2,K,Z)*(C-18)))-1)+900*@sqrt((((((9*V(2,1)+8*V(2,2))*C)
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/(15200*RATIO(2,I,2,K,Z)*(C-18)))-1)^2)+(4*((((9*V(2,1)+8*V(2,2))*C)/(15200*RATIO(2,I,2,K,Z)*(C-
18)))^2/(V(2,1)+V(2,2))))))));

@FOR(CONF_1(I):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_2(2,I,2,K,Z,2)= 0.5*C*(1-RATIO(2,I,2,K,Z)*(C-18)/C)^2/(1-
@smin(1,(V(2,3)/(3304.34*RATIO(2,I,2,K,Z)-(59478.12*RATIO(2,I,2,K,Z)/C))))*RATIO(2,I,2,K,Z)*(c-
18)/C)+900*((V(2,3)/(3304.34*RATIO(2,I,2,K,Z)-(59478.12*RATIO(2,I,2,K,Z)/C))-
1)+@sqrt(((V(2,3)/(3304.34*RATIO(2,I,2,K,Z)-(59478.12*RATIO(2,I,2,K,Z)/C))-
1)^2)+2*V(2,3)/((1652.17*RATIO(2,I,2,K,Z)-(29739.06*RATIO(2,I,2,K,Z))/C)^2))))));

@FOR(CONF_1(I):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_2(2,I,2,K,Z,3)= 0.5*C*(1-RATIO(2,I,2,K,Z)*(C-18)/C)^2/(1-
@smin(1,(V(2,3)/(3304.34*RATIO(2,I,2,K,Z)-(59478.12*RATIO(2,I,2,K,Z)/C))))*RATIO(2,I,2,K,Z)*(c-
18)/C)+900*((V(2,3)/(3304.34*RATIO(2,I,2,K,Z)-(59478.12*RATIO(2,I,2,K,Z)/C))-
1)+@sqrt(((V(2,3)/(3304.34*RATIO(2,I,2,K,Z)-(59478.12*RATIO(2,I,2,K,Z)/C))-
1)^2)+2*V(2,3)/((1652.17*RATIO(2,I,2,K,Z)-(29739.06*RATIO(2,I,2,K,Z))/C)^2))))));



@FOR(CONF_1(I):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_2(2,I,3,K,Z,1)= 0.5*C*(1-RATIO(2,I,3,K,Z)*(C-18)/C)^2/(1-
@smin(1,(V(2,1)/(3377.78*RATIO(2,I,3,K,Z)-(60800.01*RATIO(2,I,3,K,Z)/C))))*RATIO(2,I,3,K,Z)*(c-
18)/C)+900*((V(2,1)/(3377.78*RATIO(2,I,3,K,Z)-(60800.01*RATIO(2,I,3,K,Z)/C))-
1)+@sqrt(((V(2,1)/(3377.78*RATIO(2,I,3,K,Z)-(60800.01*RATIO(2,I,3,K,Z)/C))-
1)^2)+2*V(2,1)/((1688.89*RATIO(2,I,3,K,Z)-(30400.02*RATIO(2,I,3,K,Z))/C)^2))))));

@FOR(CONF_1(I):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_2(2,I,3,K,Z,2)= 0.5*C*(1-RATIO(2,I,3,K,Z)*(C-18)/C)^2/(1-
@smin(1,(V(2,1)/(3377.78*RATIO(2,I,3,K,Z)-(60800.01*RATIO(2,I,3,K,Z)/C))))*RATIO(2,I,3,K,Z)*(c-
18)/C)+900*((V(2,1)/(3377.78*RATIO(2,I,3,K,Z)-(60800.01*RATIO(2,I,3,K,Z)/C))-
1)+@sqrt(((V(2,1)/(3377.78*RATIO(2,I,3,K,Z)-(60800.01*RATIO(2,I,3,K,Z)/C))-
1)^2)+2*V(2,1)/((1688.89*RATIO(2,I,3,K,Z)-(30400.02*RATIO(2,I,3,K,Z))/C)^2))))));

@FOR(CONF_1(I):
@FOR(CONF_3(K):
@FOR(CONF_4(Z):
D_2(2,I,3,K,Z,3)= (0.5*C*(1-RATIO(2,I,3,K,Z)*(C-18)/C)^2)/(1-
(@sMin(1,(((23*V(2,3)+20*V(2,2))*C)/(38000*RATIO(2,I,3,K,Z)*(C-18))))*(RATIO(2,I,3,K,Z)*(C-
18)/C)))+ 900*((((23*V(2,3)+20*V(2,2))*C)/(38000*RATIO(2,I,3,K,Z)*(C-18)))-
1)+900*@sqrt((((((23*V(2,3)+20*V(2,2))*C/(38000*RATIO(2,I,3,K,Z)*(C-18)))-1)^2)+
(4*((((23*V(2,3)+20*V(2,2))*C)/(38000*RATIO(2,I,3,K,Z)*(C-18)))^2/(V(2,3)+V(2,2))))))));
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@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
AD(3,I,J,1,Z)= ((V(3,1)+X(3,1,1))*D_3(3,I,J,1,Z,1)+ (V(3,2)-X(3,1,1)-X(3,3,1))*D_3(3,I,J,1,Z,2)+
(V(3,3)+X(3,3,1))*D_3(3,I,J,1,Z,4))/VT(3))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
AD(3,I,J,2,Z)= ((V(3,1)+V(3,2))*D_3(3,I,J,2,Z,1)+V(3,3)*D_3(3,I,J,2,Z,2))/VT(3))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
AD(3,I,J,3,Z)=  (V(3,1)* D_3(3,I,J,3,Z,1)+(V(3,3)+V(3,2))*D_3(3,I,J,3,Z,4))/VT(3))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
AD(3,I,J,4,Z)= ((V(3,1)+X(3,1,4))*D_3(3,I,J,4,Z,1)+(V(3,2)-X(3,1,4))*D_3(3,I,J,4,Z,2)+
V(3,3)*D_3(3,I,J,4,Z,3))/VT(3))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
AD(3,I,J,5,Z)= (V(3,1)*D_3(3,I,J,5,Z,1)+(V(3,2)-X(3,3,5))* D_3(3,I,J,5,Z,3)+(V(3,3)+X(3,3,5))*
D_3(3,I,J,5,Z,4))/VT(3))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,1,Z,1)= (0.5*C*(1-RATIO(3,I,J,1,Z)*(C-18)/C)^2)/(1-(@smin(1,(((9*V(3,1)+8*X(3,1,1))*C)
/(15200*RATIO(3,I,J,1,Z)*(C-18))))*(RATIO(3,I,J,1,Z)*(C-18)/C)))+ 900*((((9*V(3,1)+8*X(3,1,1))*C)
/(15200*RATIO(3,I,J,1,Z)*(C-18)))-1)+900*@SQRT((((((9*V(3,1)+8*X(3,1,1))*C)
/(15200*RATIO(3,I,J,1,Z)*(C-18)))-1)^2)+(4*((((9*V(3,1)+8*X(3,1,1))*C)/(15200*RATIO(3,I,J,1,Z)*(C-
18)))^2/(V(3,1)+X(3,1,1))))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,1,Z,2)= 0.5*C*(1-RATIO(3,I,J,1,Z)*(C-18)/C)^2/(1-@smin(1,((V(3,2)-X(3,1,1)-
X(3,3,1))/(3800*RATIO(3,I,J,1,Z)-(68400*RATIO(3,I,J,1,Z)/C))))*RATIO(3,I,J,1,Z)*(c-18)/C)+
900*(((V(3,2)-X(3,1,1)-X(3,3,1))/(3800*RATIO(3,I,J,1,Z)-(68400*RATIO(3,I,J,1,Z)/C))-
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1)+@sqrt((((V(3,2)-X(3,1,1)-X(3,3,1))/(3800*RATIO(3,I,J,1,Z)-(68400*RATIO(3,I,J,1,Z)/C))-
1)^2)+2*(V(3,2)-X(3,1,1)-X(3,3,1))/(1900*RATIO(3,I,J,1,Z)-(34200*RATIO(3,I,J,1,Z))/C)^2)))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,1,Z,3)= 0.5*C*(1-RATIO(3,I,J,1,Z)*(C-18)/C)^2/(1-@smin(1,((V(3,2)-X(3,1,1)-
X(3,3,1))/(3800*RATIO(3,I,J,1,Z)-(68400*RATIO(3,I,J,1,Z)/C))))*RATIO(3,I,J,1,Z)*(c-18)/C)+
900*(((V(3,2)-X(3,1,1)-X(3,3,1))/(3800*RATIO(3,I,J,1,Z)-(68400*RATIO(3,I,J,1,Z)/C))-
1)+@sqrt((((V(3,2)-X(3,1,1)-X(3,3,1))/(3800*RATIO(3,I,J,1,Z)-(68400*RATIO(3,I,J,1,Z)/C))-
1)^2)+2*(V(3,2)-X(3,1,1)-X(3,3,1))/(1900*RATIO(3,I,J,1,Z)-(34200*RATIO(3,I,J,1,Z))/C)^2)))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,1,Z,4)= (0.5*C*(1-RATIO(3,I,J,1,Z)*(C-18)/C)^2)/(1-
(@sMin(1,(((23*V(3,3)+20*X(3,3,1))*C)/(38000*RATIO(3,I,J,1,Z)*(C-18))))*(RATIO(3,I,J,1,Z)*(C-
18)/C)))+ 900*((((23*V(3,3)+20*X(3,3,1))*C)/(38000*RATIO(3,I,J,1,Z)*(C-18)))-
1)+900*@sqrt((((((23*V(3,3)+20*X(3,3,1))*C)/(38000*RATIO(3,I,J,1,Z)*(C-18)))-
1)^2)+(4*((((23*V(3,3)+20*X(3,3,1))*C)/(38000*RATIO(3,I,J,1,Z)*(C-18)))^2/(V(3,3)+X(3,3,1))))))));


@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,2,Z,1)= (0.5*C*(1-RATIO(3,I,J,2,Z)*(C-18)/C)^2)/(1-(@smin(1,(((9*V(3,1)+8*V(3,2))*C)
/(15200*RATIO(3,I,J,2,Z)*(C-18))))*(RATIO(3,I,J,2,Z)*(C-18)/C)))+ 900*((((9*V(3,1)+8*V(3,2))*C)
/(15200*RATIO(3,I,J,2,Z)*(C-18)))-1)+900*@sqrt((((((9*V(3,1)+8*V(3,2))*C)
/(15200*RATIO(3,I,J,2,Z)*(C-18)))-1)^2)+(4*((((9*V(3,1)+8*V(3,2))*C)/(15200*RATIO(3,I,J,2,Z)*(C-
18)))^2/(V(3,1)+V(3,2))))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,2,Z,2)= 0.5*C*(1-RATIO(3,I,J,2,Z)*(C-18)/C)^2/(1-
@smin(1,(V(3,3)/(4956.51*RATIO(3,I,J,2,Z)-(89217.18*RATIO(3,I,J,2,Z)/C))))*RATIO(3,I,J,2,Z)*(c-
18)/C)+900*((V(3,3)/(4956.51*RATIO(3,I,J,2,Z)-(89217.18*RATIO(3,I,J,2,Z)/C))-
1)+@sqrt(((V(3,3)/(4956.51*RATIO(3,I,J,2,Z)-(89217.18*RATIO(3,I,J,2,Z)/C))-
1)^2)+4*V(3,3)/(3*(1652.17*RATIO(3,I,J,2,Z)-(29739.06*RATIO(3,I,J,2,Z))/C)^2))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,2,Z,3)= 0.5*C*(1-RATIO(3,I,J,2,Z)*(C-18)/C)^2/(1-
@smin(1,(V(3,3)/(4956.51*RATIO(3,I,J,2,Z)-(89217.18*RATIO(3,I,J,2,Z)/C))))*RATIO(3,I,J,2,Z)*(c-
18)/C)+900*((V(3,3)/(4956.51*RATIO(3,I,J,2,Z)-(89217.18*RATIO(3,I,J,2,Z)/C))-
1)+@sqrt(((V(3,3)/(4956.51*RATIO(3,I,J,2,Z)-(89217.18*RATIO(3,I,J,2,Z)/C))-
1)^2)+4*V(3,3)/(3*(1652.17*RATIO(3,I,J,2,Z)-(29739.06*RATIO(3,I,J,2,Z))/C)^2))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
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@FOR(CONF_4(Z):
D_3(3,I,J,2,Z,4)= 0.5*C*(1-RATIO(3,I,J,2,Z)*(C-18)/C)^2/(1-@smin(1,(V(3,3)/(4956.51*RATIO(3,I,J,2,Z)-(89217.18*RATIO(3,I,J,2,Z)/C))))*RATIO(3,I,J,2,Z)*(c-18)/C)+900*((V(3,3)/(4956.51*RATIO(3,I,J,2,Z)-(89217.18*RATIO(3,I,J,2,Z)/C))-1)+@sqrt(((V(3,3)/(4956.51*RATIO(3,I,J,2,Z)-(89217.18*RATIO(3,I,J,2,Z)/C))-1)^2)+4*V(3,3)/(3*(1652.17*RATIO(3,I,J,2,Z)-(29739.06*RATIO(3,I,J,2,Z))/C)^2))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,3,Z,1)= 0.5*C*(1-RATIO(3,I,J,3,Z)*(C-18)/C)^2/(1-@smin(1,(V(3,1)/(5066.67*RATIO(3,I,J,3,Z)-(91200.06*RATIO(3,I,J,3,Z)/C))))*RATIO(3,I,J,3,Z)*(c-18)/C)+900*((V(3,1)/(5066.67*RATIO(3,I,J,3,Z)-(91200.06*RATIO(3,I,J,3,Z)/C))-1)+@sqrt(((V(3,1)/(5066.67*RATIO(3,I,J,3,Z)-(91200.06*RATIO(3,I,J,3,Z)/C))-1)^2)+4*V(3,1)/(3*(1688.89*RATIO(3,I,J,3,Z)-(30400.02*RATIO(3,I,J,3,Z))/C)^2))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,3,Z,2)= 0.5*C*(1-RATIO(3,I,J,3,Z)*(C-18)/C)^2/(1-@smin(1,(V(3,1)/(5066.67*RATIO(3,I,J,3,Z)-(91200.06*RATIO(3,I,J,3,Z)/C))))*RATIO(3,I,J,3,Z)*(c-18)/C)+900*((V(3,1)/(5066.67*RATIO(3,I,J,3,Z)-(91200.06*RATIO(3,I,J,3,Z)/C))-1)+@sqrt(((V(3,1)/(5066.67*RATIO(3,I,J,3,Z)-(91200.06*RATIO(3,I,J,3,Z)/C))-1)^2)+4*V(3,1)/(3*(1688.89*RATIO(3,I,J,3,Z)-(30400.02*RATIO(3,I,J,3,Z))/C)^2))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,3,Z,3)= 0.5*C*(1-RATIO(3,I,J,3,Z)*(C-18)/C)^2/(1-@smin(1,(V(3,1)/(5066.67*RATIO(3,I,J,3,Z)-(91200.06*RATIO(3,I,J,3,Z)/C))))*RATIO(3,I,J,3,Z)*(c-18)/C)+900*((V(3,1)/(5066.67*RATIO(3,I,J,3,Z)-(91200.06*RATIO(3,I,J,3,Z)/C))-1)+@sqrt(((V(3,1)/(5066.67*RATIO(3,I,J,3,Z)-(91200.06*RATIO(3,I,J,3,Z)/C))-1)^2)+4*V(3,1)/(3*(1688.89*RATIO(3,I,J,3,Z)-(30400.02*RATIO(3,I,J,3,Z))/C)^2))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,3,Z,4)= (0.5*C*(1-RATIO(3,I,J,3,Z)*(C-18)/C)^2)/(1-(@sMin(1,(((23*V(3,3)+20*V(3,2))*C)/(38000*RATIO(3,I,J,3,Z)*(C-18)))))*(RATIO(3,I,J,3,Z)*(C-18)/C)))+ 900*((((23*V(3,3)+20*V(3,2))*C)/(38000*RATIO(3,I,J,3,Z)*(C-18)))-1)+900*@sqrt((((((23*V(3,3)+20*V(3,2))*C/(38000*RATIO(3,I,J,3,Z)*(C-18)))-1)^2)+(4*((((23*V(3,3)+20*V(3,2))*C)/(38000*RATIO(3,I,J,3,Z)*(C-18)))^2/(V(3,3)+V(3,2)))))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):

```
D_3(3,I,J,4,Z,1)= (0.5*C*(1-RATIO(3,I,J,4,Z)*(C-18)/C)^2)/(1-(@smin(1,(((9*V(3,1)+8*X(3,1,4))*C)
/(15200*RATIO(3,I,J,4,Z)*(C-18))))*(RATIO(3,I,J,4,Z)*(C-18)/C)))+ 900*((((9*V(3,1)+8*X(3,1,4))*C)
/(15200*RATIO(3,I,J,4,Z)*(C-18)))-1)+900*@SQRT((((((9*V(3,1)+8*X(3,1,4))*C)
/(15200*RATIO(3,I,J,4,Z)*(C-18)))-1)^2)+(4*((((9*V(3,1)+8*X(3,1,4))*C)/(15200*RATIO(3,I,J,4,Z)*(C-
18)))^2/(V(3,1)+X(3,1,4))))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,4,Z,2)= 0.5*C*(1-RATIO(3,I,J,4,Z)*(C-18)/C)^2/(1-@smin(1,((V(3,2)-
X(3,1,4))/(1900*RATIO(3,I,J,4,Z)-(34200*RATIO(3,I,J,4,Z)/C))))*RATIO(3,I,J,4,Z)*(c-18)/C)+
900*(((V(3,2)-X(3,1,4))/(1900*RATIO(3,I,J,4,Z)-(34200*RATIO(3,I,J,4,Z)/C))-1)+@sqrt((((V(3,2)-
X(3,1,4))/(1900*RATIO(3,I,J,4,Z)-(34200*RATIO(3,I,J,4,Z)/C))-1)^2)+4*(V(3,2)-
X(3,1,4))/(1900*RATIO(3,I,J,4,Z)-(34200*RATIO(3,I,J,4,Z))/C)^2))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,4,Z,3)= 0.5*C*(1-RATIO(3,I,J,4,Z)*(C-18)/C)^2/(1-
@smin(1,(V(3,3)/(3304.34*RATIO(3,I,J,4,Z)-(59478.12*RATIO(3,I,J,4,Z)/C))))*RATIO(3,I,J,4,Z)*(c-
18)/C)+900*((V(3,3)/(3304.34*RATIO(3,I,J,4,Z)-(59478.12*RATIO(3,I,J,4,Z)/C))-
1)+@sqrt(((V(3,3)/(3304.34*RATIO(3,I,J,4,Z)-(59478.12*RATIO(3,I,J,4,Z)/C))-
1)^2)+2*V(3,3)/(1652.17*RATIO(3,I,J,4,Z)-(29739.06*RATIO(3,I,J,4,Z))/C)^2)))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,4,Z,4)= 0.5*C*(1-RATIO(3,I,J,4,Z)*(C-18)/C)^2/(1-
@smin(1,(V(3,3)/(3304.34*RATIO(3,I,J,4,Z)-(59478.12*RATIO(3,I,J,4,Z)/C))))*RATIO(3,I,J,4,Z)*(c-
18)/C)+900*((V(3,3)/(3304.34*RATIO(3,I,J,4,Z)-(59478.12*RATIO(3,I,J,4,Z)/C))-
1)+@sqrt(((V(3,3)/(3304.34*RATIO(3,I,J,4,Z)-(59478.12*RATIO(3,I,J,4,Z)/C))-
1)^2)+2*V(3,3)/(1652.17*RATIO(3,I,J,4,Z)-(29739.06*RATIO(3,I,J,4,Z))/C)^2)))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,5,Z,1)= 0.5*C*(1-RATIO(3,I,J,5,Z)*(C-18)/C)^2/(1-
@smin(1,(V(3,1)/(3377.78*RATIO(3,I,J,5,Z)-(60800.04*RATIO(3,I,J,5,Z)/C))))*RATIO(3,I,J,5,Z)*(c-
18)/C)+900*((V(3,1)/(3377.78*RATIO(3,I,J,5,Z)-(60800.04*RATIO(3,I,J,5,Z)/C))-
1)+@sqrt(((V(3,1)/(3377.78*RATIO(3,I,J,5,Z)-(60800.04*RATIO(3,I,J,5,Z)/C))-
1)^2)+2*V(3,1)/(1688.89*RATIO(3,I,J,5,Z)-(30400.02*RATIO(3,I,J,5,Z))/C)^2)))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,5,Z,2)= 0.5*C*(1-RATIO(3,I,J,5,Z)*(C-18)/C)^2/(1-
@smin(1,(V(3,1)/(3377.78*RATIO(3,I,J,5,Z)-(60800.04*RATIO(3,I,J,5,Z)/C))))*RATIO(3,I,J,5,Z)*(c-
18)/C)+900*((V(3,1)/(3377.78*RATIO(3,I,J,5,Z)-(60800.04*RATIO(3,I,J,5,Z)/C))-
1)+@sqrt(((V(3,1)/(3377.78*RATIO(3,I,J,5,Z)-(60800.04*RATIO(3,I,J,5,Z)/C))-
1)^2)+2*V(3,1)/(1688.89*RATIO(3,I,J,5,Z)-(30400.02*RATIO(3,I,J,5,Z))/C)^2)))));
```

```
@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,5,Z,3)= 0.5*C*(1-RATIO(3,I,J,5,Z)*(C-18)/C)^2/(1-@smin(1,((V(3,2)-
X(3,3,5))/(1900*RATIO(3,I,J,5,Z)-(34200*RATIO(3,I,J,5,Z)/C))))*RATIO(3,I,J,5,Z)*(c-18)/C)+
900*(((V(3,2)-X(3,3,5))/(1900*RATIO(3,I,J,5,Z)-(34200*RATIO(3,I,J,5,Z)/C))-1)+@sqrt((((V(3,2)-
X(3,3,5))/(1900*RATIO(3,I,J,5,Z)-(34200*RATIO(3,I,J,5,Z)/C))-1)^2)+4*(V(3,2)-
X(3,3,5))/(1900*RATIO(3,I,J,5,Z)-(34200*RATIO(3,I,J,5,Z))/C)^2)))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_4(Z):
D_3(3,I,J,5,Z,4)= (0.5*C*(1-RATIO(3,I,J,5,Z)*(C-18)/C)^2)/(1-
(@sMin(1,(((23*V(3,3)+20*X(3,3,5))*C)/(38000*RATIO(3,I,J,5,Z)*(C-18))))*(RATIO(3,I,J,5,Z)*(C-
18)/C)))+ 900*((((23*V(3,3)+20*X(3,3,5))*C)/(38000*RATIO(3,I,J,5,Z)*(C-18)))-
1)+900*@sqrt((((((23*V(3,3)+20*X(3,3,5))*C)/(38000*RATIO(3,I,J,5,Z)*(C-18)))-
1)^2)+(4*((((23*V(3,3)+20*X(3,3,5))*C)/(38000*RATIO(3,I,J,5,Z)*(C-18)))^2/(V(3,3)+X(3,3,5))))))));


@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_3(K):
AD(4,I,J,K,1)= ((V(4,1)+X(4,1,1))*D_4(4,I,J,K,1,1)+(V(4,2)-X(4,1,1))*D_4(4,I,J,K,1,2)+
(V(4,3)+X(4,3,1))*D_4(4,I,J,K,1,3))/VT(4))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_3(K):
AD(4,I,J,K,2)= ((V(4,1)+V(4,2))*D_4(4,I,J,K,2,1)+ V(4,3)*D_4(4,I,J,K,2,2))/VT(4))));



@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_3(K):
AD(4,I,J,K,3)= (V(4,1)*D_4(4,I,J,K,3,1)+(V(4,3)+V(4,2))*D_4(4,I,J,K,3,3))/VT(4))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_3(K):
D_4(4,I,J,K,1,1)= (0.5*C*(1-RATIO(4,I,J,K,1)*(C-18)/C)^2)/(1-
(@smin(1,(((9*V(4,1)+8*X(4,1,1))*C)  /(15200*RATIO(4,I,J,K,1)*(C-18))))*(RATIO(4,I,J,K,1)*(C-
18)/C)))+ 900*((((9*V(4,1)+8*X(2,1,1))*C)  /(15200*RATIO(4,I,J,K,1)*(C-18)))-
1)+900*@SQRT((((((9*V(4,1)+8*X(2,1,1))*C)  /(15200*RATIO(4,I,J,K,1)*(C-18)))-
1)^2)+(4*((((9*V(4,1)+8*X(2,1,1))*C)/(15200*RATIO(4,I,J,K,1)*(C-18)))^2/(V(4,1)+X(2,1,1))))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_3(K):
```

```
D_4(4,I,J,K,1,2)= 0.5*C*(1-RATIO(4,I,J,K,1)*(C-18)/C)^2/(1-@smin(1,((V(4,2)-X(4,1,1)-
X(4,3,1))/(1900*RATIO(4,I,J,K,1)-(34200*RATIO(4,I,J,K,1)/C))))*RATIO(4,I,J,K,1)*(c-18)/C)+
900*(((V(4,2)-X(4,1,1)-X(4,3,1))/(1900*RATIO(4,I,J,K,1)-(34200*RATIO(4,I,J,K,1)/C))-
1)+@sqrt((((V(4,2)-X(4,1,1)-X(4,3,1))/(1900*RATIO(4,I,J,K,1)-(34200*RATIO(4,I,J,K,1)/C))-
1)^2)+4*(V(4,2)-X(4,1,1)-X(4,3,1))/(1900*RATIO(4,I,J,K,1)-(34200*RATIO(4,I,J,K,1))/C)^2)))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_3(K):
D_4(4,I,J,K,1,3)= (0.5*C*(1-RATIO(4,I,J,K,1)*(C-18)/C)^2)/(1-
(@sMin(1,(((23*V(4,3)+20*X(4,3,1))*C)/(38000*RATIO(4,I,J,K,1)*(C-18))))*(RATIO(4,I,J,K,1)*(C-
18)/C)))+ 900*((((23*V(4,3)+20*X(4,3,1))*C)/(38000*RATIO(4,I,J,K,1)*(C-18)))-
1)+900*@sqrt((((((23*V(4,3)+20*X(4,3,1))*C)/(38000*RATIO(4,I,J,K,1)*(C-18)))-
1)^2)+(4*((((23*V(4,3)+20*X(4,3,1))*C)/(38000*RATIO(4,I,J,K,1)*(C-18)))^2/(V(4,3)+X(4,3,1))))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_3(K):
D_4(4,I,J,K,2,1)= (0.5*C*(1-RATIO(4,I,J,K,2)*(C-18)/C)^2)/(1-(@smin(1,(((9*V(4,1)+8*V(4,2))*C)
/(15200*RATIO(4,I,J,K,2)*(C-18))))*(RATIO(4,I,J,K,2)*(C-18)/C)))+ 900*((((9*V(4,1)+8*V(4,2))*C)
/(15200*RATIO(4,I,J,K,2)*(C-18)))-1)+900*@sqrt((((((9*V(4,1)+8*V(4,2))*C)
/(15200*RATIO(4,I,J,K,2)*(C-18)))-1)^2)+(4*((((9*V(4,1)+8*V(4,2))*C)/(15200*RATIO(4,I,J,K,2)*(C-
18)))^2/(V(4,1)+V(4,2))))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_3(K):
D_4(4,I,J,K,2,2)= 0.5*C*(1-RATIO(4,I,J,K,2)*(C-18)/C)^2/(1-
@smin(1,(V(4,3)/(3304.34*RATIO(4,I,J,K,2)-(59478.12*RATIO(4,I,J,K,2)/C))))*RATIO(4,I,J,K,2)*(c-
18)/C)+900*((V(4,3)/(3304.34*RATIO(4,I,J,K,2)-(59478.12*RATIO(4,I,J,K,2)/C))-
1)+@sqrt(((V(4,3)/(3304.34*RATIO(4,I,J,K,2)-(59478.12*RATIO(4,I,J,K,2)/C))-
1)^2)+2*V(4,3)/((1652.17*RATIO(4,I,J,K,2)-(29739.06*RATIO(4,I,J,K,2))/C)^2))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_3(K):
D_4(4,I,J,K,2,3)= 0.5*C*(1-RATIO(4,I,J,K,2)*(C-18)/C)^2/(1-
@smin(1,(V(4,3)/(3304.34*RATIO(4,I,J,K,2)-(59478.12*RATIO(4,I,J,K,2)/C))))*RATIO(4,I,J,K,2)*(c-
18)/C)+900*((V(4,3)/(3304.34*RATIO(4,I,J,K,2)-(59478.12*RATIO(4,I,J,K,2)/C))-
1)+@sqrt(((V(4,3)/(3304.34*RATIO(4,I,J,K,2)-(59478.12*RATIO(4,I,J,K,2)/C))-
1)^2)+2*V(4,3)/((1652.17*RATIO(4,I,J,K,2)-(29739.06*RATIO(4,I,J,K,2))/C)^2))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_3(K):
D_4(4,I,J,K,3,1)= 0.5*C*(1-RATIO(4,I,J,K,3)*(C-18)/C)^2/(1-
@smin(1,(V(4,1)/(3377.78*RATIO(4,I,J,K,3)-(60800.04*RATIO(4,I,J,K,3)/C))))*RATIO(4,I,J,K,3)*(c-
18)/C)+900*((V(4,1)/(3377.78*RATIO(4,I,J,K,3)-(60800.04*RATIO(4,I,J,K,3)/C))-
1)+@sqrt(((V(4,1)/(3377.78*RATIO(4,I,J,K,3)-(60800.04*RATIO(4,I,J,K,3)/C))-
1)^2)+2*V(4,1)/((1688.89*RATIO(4,I,J,K,3)-(30400.02*RATIO(4,I,J,K,3))/C)^2))))));
```

```
@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_3(K):
D_4(4,I,J,K,3,2)= 0.5*C*(1-RATIO(4,I,J,K,3)*(C-18)/C)^2/(1-
@smin(1,(V(4,1)/(3377.78*RATIO(4,I,J,K,3)-(60800.04*RATIO(4,I,J,K,3)/C))))*RATIO(4,I,J,K,3)*(c-
18)/C)+900*((V(4,1)/(3377.78*RATIO(4,I,J,K,3)-(60800.04*RATIO(4,I,J,K,3)/C))-
1)+@sqrt(((V(4,1)/(3377.78*RATIO(4,I,J,K,3)-(60800.04*RATIO(4,I,J,K,3)/C))-
1)^2)+2*V(4,1)/((1688.89*RATIO(4,I,J,K,3)-(30400.02*RATIO(4,I,J,K,3))/C)^2))))));

@FOR(CONF_1(I):
@FOR(CONF_2(J):
@FOR(CONF_3(K):
D_4(4,I,J,K,3,3)= (0.5*C*(1-RATIO(4,I,J,K,3)*(C-18)/C)^2)/(1-
(@sMin(1,(((23*V(4,3)+20*V(4,2))*C)/(38000*RATIO(4,I,J,K,3)*(C-18))))*(RATIO(4,I,J,K,3)*(C-
18)/C)))+ 900*((((23*V(4,3)+20*V(4,2))*C)/(38000*RATIO(4,I,J,K,3)*(C-18)))-
1)+900*@sqrt((((((23*V(4,3)+20*V(4,2))*C/(38000*RATIO(4,I,J,K,3)*(C-18)))-1)^2)+
(4*((((23*V(4,3)+20*V(4,2))*C)/(38000*RATIO(4,I,J,K,3)*(C-18)))^2/(V(4,3)+V(4,2))))))))));



SUBMODEL SS:
CL = 80; CR = 120;

TAU=0.618;
C1=TAU*CL+(1-TAU)*CR;
C2=(1-TAU)*CL+TAU*CR;
ENDSUBMODEL

CALC:
@solve(ss);
ENDCALC

CALC:
C=C1;
@SOLVE();
ENDCALC

CALC:
D1=Y;
ENDCALC

CALC:
C=C2;
@SOLVE();
ENDCALC

CALC:
D2=Y;
ENDCALC


CALC:
@WHILE(CR-CL #GT# 1:
CR=@IF(D2 #GE# D1,C2,CR);
```

```
CL=@IF(D2 #GE# D1,CL,C1);
!TAU=0.618;
!C1=@IF(D2 #GE# D1,TAU*CL+(1-TAU)*CR,C2);
C1=TAU*CL+(1-TAU)*CR;
C2=(1-TAU)*CL+TAU*CR;
C=C1;
@SOLVE();
D1=Y;
!C2=@IF(D2 #GE# D1,C1,(1-TAU)*CL+TAU*CR);
C=C2;
@SOLVE();
D2=Y;
@WRITE('CL = ',CL,'; CR = ',CR,@NEWLINE(1));
@WRITE('B(1,3,4,3) = ',B(1,3,4,3) ,'; B(5,3,4,3)  = ',B(5,3,4,3) ,@NEWLINE(1));


);
ENDCALC

END

DATA:
V=
400, 400,200
300, 100 , 200
200, 100 , 250
400, 100 , 300;
X=
```

0.00000	0.00000	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000

```
;

ENDDATA
```

Appendix C : The Questionnaire Survey

King Fahd University of Petroleum and Minerals

Questionnaire survey

This study aims to examine the drivers' response to variable message signs when applying dynamic lane grouping DLG at signalized intersections. DLG is an intelligent transportation system technique which can be used to optimize the lane assignment based on the traffic movement demand during the day. This survey aim for research purposes only. You will remain anonymous and the information will be kept confidential and will not be given to any other party.

Part 1: Personal Information

1. **What is your age?**

☐ >16-24 years old
☐ >24-34 years old
☐ >34-44 years old
☐ >44-54 years old
☐ >54-64 years old
☐ >64 years old

2. **What is the highest degree or level of school you have completed?**

☐ Elementary school or less
☐ High school graduate/ diploma
☐ Bachelor's degree
☐ Master's degree
☐ Doctorate degree

3. **What is your occupation?**

☐ Faculty Member
☐ Staff Member
☐ Student
☐ Chauffer

4. **What is your driving experience in years?** ( ) years

Part 2: Driver Response to Variable Message Signs:

- To answer questions (5-7), please see video #1.

1 2 3 4

5. Which lane you will use to make left turn maneuver?

☐ 1 ☐ 2 ☐3 ☐4

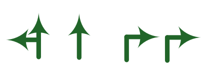
6. Which lane you will use to make right turn maneuver?

☐ 1 ☐ 2 ☐ 3 ☐ 4

7. Which lane you will use to go straight?

☐ 1 ☐ 2 ☐ 3 ☐ 4

- To answer questions (8-10), please see video #2.



1 2 3 4

8. Which lane you will use to make left turn maneuver?

☐ 1 ☐ 2 ☐3 ☐4

9. Which lane you will use to make right turn maneuver?

☐ 1 ☐ 2 ☐3 ☐4

10. Which lane you will use to go straight?

☐ 1 ☐ 2 ☐3 ☐4

Thank you for your time

Vitae

Name :Khaled Jamal Assi

Nationality :Jordanian

Date of Birth :5/7/1988

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Address :Ramallah-Palestine

EDUCATION

Feb 2014 – Present

PhD in Transportation Engineering **3.81 out of 4**

King Fahd University of Petroleum and Minerals – Saudi Arabia.

Thesis title:

"Application of Dynamic Lane Grouping and Artificial Intelligence Techniques in Predicting the Optimum Lane Groups at Isolated Signalized Intersections"

Jan 2012 – Jan 2014

M.Sc. Degree in Transportation Engineering. **3.86 out of 4**

King Fahd University of Petroleum and Minerals (KFUPM) – Saudi Arabia.

Thesis title:

"The Effect of Local Schools' Traffic on Congestion of Urban Networks"

Sep 2006 – Jan 2011

Bachelor Degree in Civil Engineering. **86% with distinction**

Birzeit University – Palestine.

WORK EXPERIENCE

Feb 2014 –Present

Lecturer

King Fahd University of Petroleum and Minerals (KFUPM) – Saudi Arabia.

- Teaching transportation courses such as Surveying and Transportation Engineering at undergraduate level.
- Supervise or assist in the supervision of undergraduate students
- Participate in the development, administration and marking of exams and other assessments.
- Carry out research and produce publications

Jan 2012 –Jan 2014

Teaching Assistant

King Fahd University of Petroleum and Minerals (KFUPM) – Saudi Arabia.

- Preparation and supervision of Civil engineering various labs (Transportation Engineering labs and Surveying labs).
- Preparation and evaluation of quizzes and homework.
- Help and guide students in using engineering equipment, collect data and analyze it.

Feb 2011 –Oct 2011 **Site Engineer**

Union Construction and Investment – Palestinian.

- Supervision of structural elements construction, concrete pouring and its quality, formwork and finishing.
- Management of all construction works, with max overlapping between works and best quality without losing time or money.

Publications

1. Ratrout, N.T. and Assi, K.J.. Parking Generation Models for Public and Private Schools: A Comparison Study. Institute of Transportation Engineers. ITE Journal, 2016, Volume 86, Issue 3, p. 44.

2. Alhajyaseen, W.K., Ratrout, N.T., Assi, K.J., and Hassan, A.A. The Integration of Dynamic Lane Grouping Technique and Signal Timing Optimization for Improving the Mobility of Isolated Intersections. Arabian Journal for Science and Engineering, 2016, 1-12.

3. Ratrout, N.T., Gazder, U., and Assi, K.J. Effect of Public Transportation in Reducing Passenger Car Trips to Schools in Al-Khobar–Dhahran metropolitan area, Saudi Arabia. Transportation Letters, 2016, 1-9.

4. Alhajyaseen, W.K.M., Najjar, M., Ratrout, N.T., and Assi, K. The Effectiveness of Applying Dynamic Lane Assignment at All Approaches of Signalized Intersection. Case Studies on Transport Policy http://dx.doi.org/10.1016/j.cstp.2017.01.008

5. Alhajyaseen, W., Najjar, M.M.. Ratrout, N.T., and Assi, K.J. "The Effectiveness of Applying Dynamic Lane Assignment at All Approaches of Signalized Intersection". Accepted for publication in Transport Research Procedia in February, 2016.

6. Ratrout, N.T., Assi, K.J., and Gazder, U. Schools' Trip Generation Models: A Comparison Study. Journal of Civil Engineering & Management **(Under Review)**. Submitted in December 2016.

7. Assi, K.J. and Ratrout, N.T. Proposed Quick Method for Applying Dynamic Lane Grouping at Signalized Intersections. IATSS Research **(Under Review)**. Submitted in December 2016.

8. Assi, K.J., Nahidudzaman, K.H., Ratrout, N.T., and Aldosary, A. Mode Choice Behavior of the High School Goers: Evaluating Logistic Regression and MLP Neural Networks Case Studies on Transport Policy **(Under Review)**. Submitted in November 2016.

Research Projects

1. Traffic Impact for Akwan Housing Project, Dammam, (Researcher), Project # CE2374, KFUPM, March 2015, Total budget: SR 170,000.
2. Development of Demand Responsive Dynamic Lane Assignment Strategy for Signalized Intersections, (Researcher), KFUPM, Dhahran, Project # IN131009, KFUPM, September 2013, Budget: SR 366,900.
3. Impact of Schools on Urban Traffic in Khobar-Dhahran areas Saudi Arabia, (Research Assistant), Project # IN131008, KFUPM, November 2014, Total budget: SR 41,360.